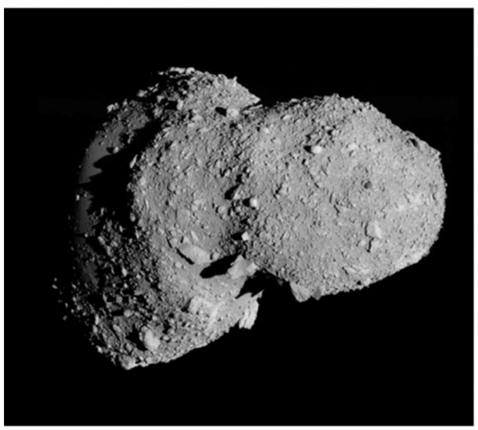
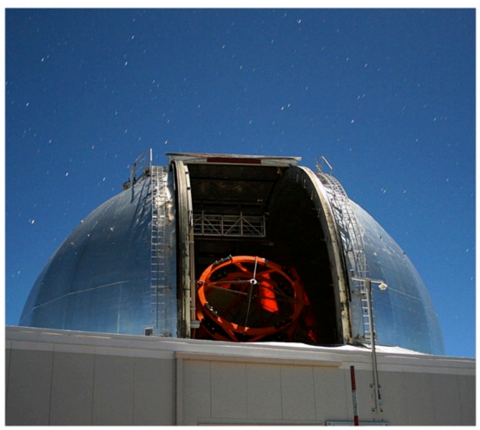
National Aeronautics and Space Administration

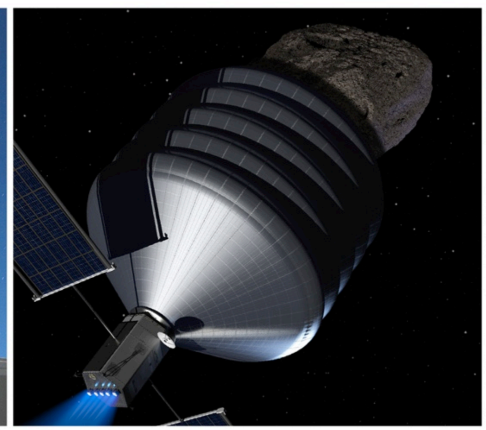
Asteroid Initiative Opportunities Forum
Update on Asteroid Redirect Mission

Michele Gates, Moderator
Panelists: Lindley Johnson, Brian Muirhead, Dan Mazanek, Jim Reuter, Steve Stich, Jason Crusan

March 26, 2014







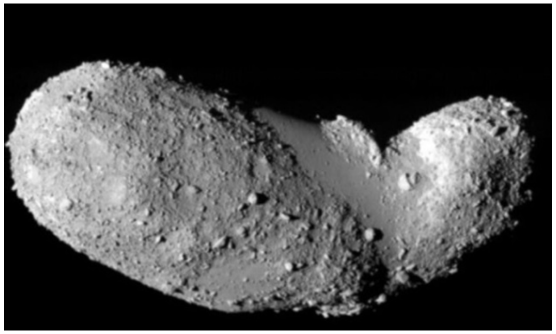
Preliminary Objectives of Asteroid Redirect Mission

- **Primary Objectives**
  - Human Exploration
    - To an Asteroid in the mid-2020's that prepares for future exploration
      - System and component development, operational experience beyond LEO, crew risk reduction
  - Technology Demonstration: Advanced Solar Electric Propulsion
    - High power, long lifetime
  - Enhanced Detection and Observation of Near Earth Asteroids for Planetary Defense
- **Secondary Objectives**
  - Asteroid Deflection Demonstration/Proof of Concept for Planetary Defense
  - Science
  - Future Commercial Use
  - Future Resource Use
  - Partnership Opportunities (International and Commercial)
- **Ground Rules**
  - Affordability
  - Manageable Technical Risk Tolerance
  - Programmatic Viability

Reference: Early Concept Studies and Ideas Synthesis Workshop

NASA Asteroid Redirect Mission Internal Studies Completed

Reference robotic mission concept
- To redirect a small near Earth asteroid and potentially demonstrate asteroid deflection
- Study led by the Jet Propulsion Laboratory



Alternate robotic mission concept
- To redirect a boulder from a larger asteroid and potentially demonstrate asteroid deflection
- Study led by the Langley Research Center

Crewed Mission
- Crew rendezvous and sampling for either concept
- Led by the Johnson Space Center

Robotic Concept Integration Team comparative assessment

Revised Objectives of Asteroid Redirect Mission

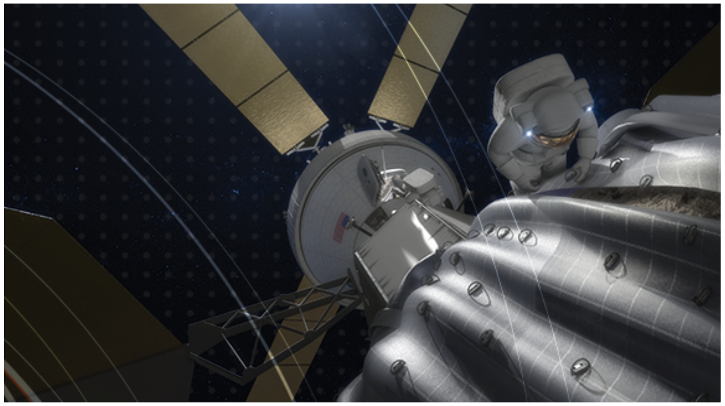
- Conduct a human exploration mission to an asteroid in the mid-2020's, providing systems and operational experience required for human exploration of Mars.

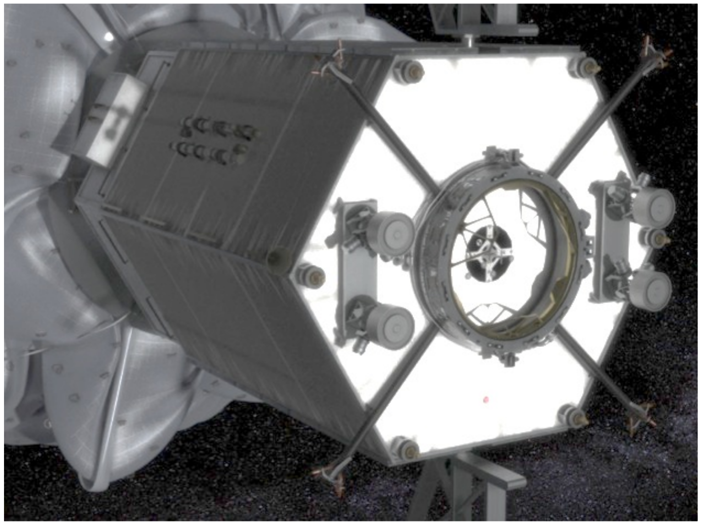
- Demonstrate an advanced solar electric propulsion system, enabling future deep-space human and robotic exploration with applicability to the nation's public and private sector space needs.

- Enhance detection, tracking and characterization of Near Earth Asteroids, enabling an overall strategy to defend our home planet.

- Demonstrate basic planetary defense techniques that will inform impact threat mitigation strategies to defend our home planet.

- Pursue a target of opportunity that benefits scientific and partnership interests, expanding our knowledge of small celestial bodies and enabling the mining of asteroid resources for commercial and exploration needs.





ARM Concepts Near Term Schedule

• Request for Information Release	Jun 18, 2013
• NASA Internal Concepts Review	Jul 30, 2013
• Ideas Synthesis Part 1 (RFI responses)	Sep 30, 2013
• Robotic Concept Integration Team Kicked Off	Oct 25, 2013
• Ideas Synthesis Resumed (RFI responses)	Nov 20-22, 2013
• NASA Internal Integrated Status Review	Dec 17, 2013
• Tasking Request for External Community Special Studies	Jan 8, 2014
• Spitzer Observation of 2011 MD	Feb 9, 2014
• NASA Internal Mission Concept Development Review	Feb 19, 2014
• Broad Agency Announcement Release	Mar 21, 2014

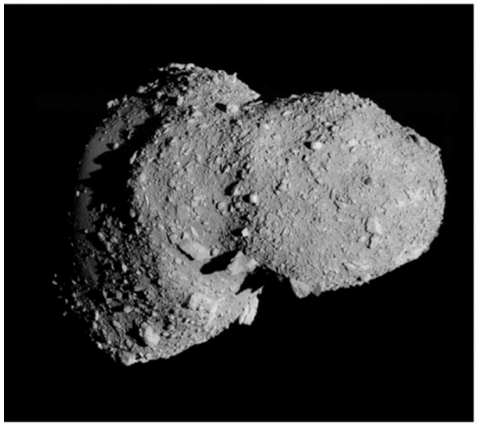
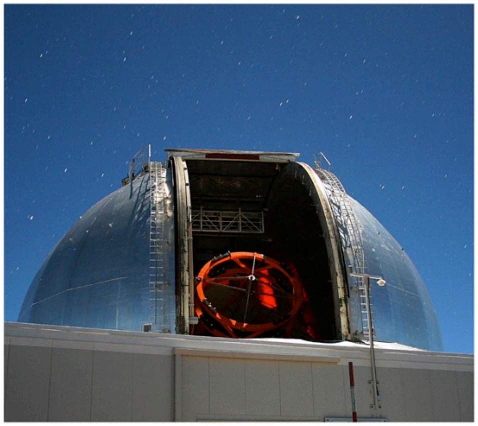
• Asteroid Initiative Opportunities Forum in Washington DC	Mar 26, 2014
• BAA Awards	NET Jul 1, 2014
• STMD Solar Array Systems development Phase 1 complete	Apr 2014
• STMD Integrated Thruster performance Test with 120V PPU	Sept 2014
• HEOMD MACES EVA end-to-end mission Sim Complete	Sept 2014
• BAA Interim Reports Due	Oct 31, 2014
• HEOMD Orion Exploration Flight Test 1	Dec 2014
• BAA Period of Performance Ends	Dec 31, 2014
• Robotic Mission Concept Review	Early 2015

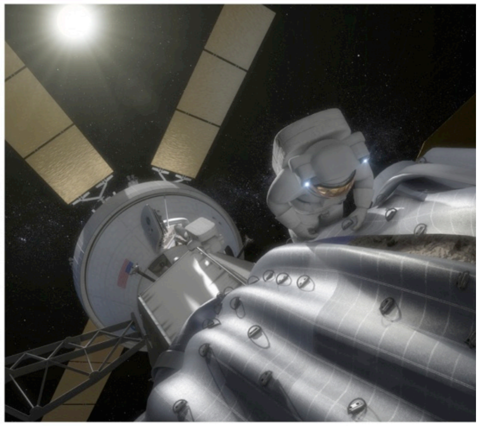
National Aeronautics and Space Administration

Observation Campaign Status and Opportunity

Lindley Johnson (NEO Program Executive)

March 26, 2014

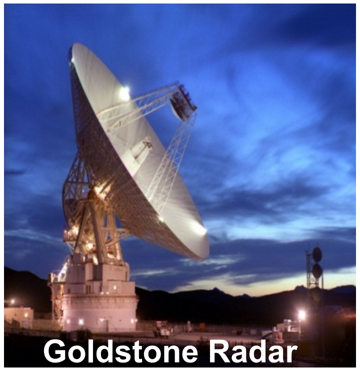


Observation Campaign Status

Since Asteroid Initiative was announced (April 2013)

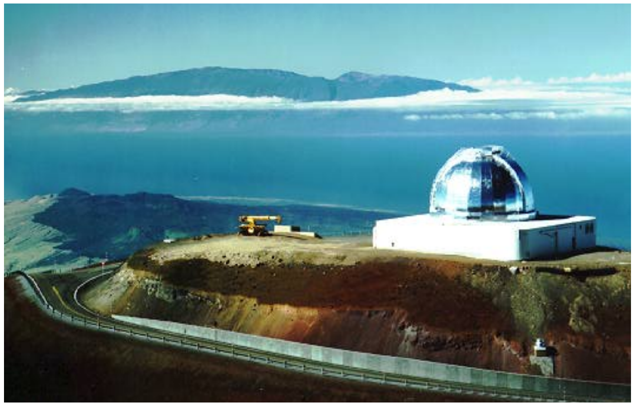
- 1,010 more Near Earth Asteroids (NEAs) have been found by search teams
  - Catalina Sky Survey 59%
  - Pan-STARRS 34%
  - LINEAR 1% (converting to new Space Surveillance Telescope)
  - Spacewatch 2% (no longer a full time search asset)
  - NEO WISE 1% (reactivated December 2013)
  - Other 3%
- Only 11 greater than 1 kilometer in size. This population becoming well known
- 73 are in orbits potentially hazardous to the Earth (PHAs)
  - Only 1 is greater than 1 kilometer in size
- 36 are potentially spacecraft accessible (round trip delta V < 8 km/sec)
  - But only 20 in next 10 years (2015-2025)
- Of the 20, only 8 are estimated to perhaps be small enough for capture, but **none** have another opportunity to be adequately characterized using existing assets (largely ground-based)
- Of the 20, only 9 might make good candidates for boulder retrieval, but only **2** have another opportunity to be adequately characterized using existing assets (largely ground-based)

Primary NEO Characterization Assets and Enhancements



Radar (Goldstone and Arecibo)

- Increased time for NEO observations
- Streamlining Rapid Response capabilities
- Improve maintainability

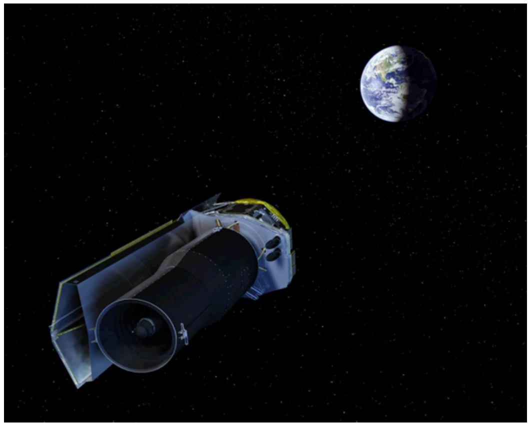


NASA InfraRed Telescope Facility (IRTF)

- Increased call-up for Rapid Response
- Improving operability/maintainability
- Improve Instrumentation for Spectroscopy and Thermal Signatures

Spitzer Infrared Space Telescope

- Orbit about Sun, ~176 million km trailing Earth
- In extended Warm-phase mission
- Characterization of Comets and Asteroids
- Thermal Signatures, Albedo/Sizes of NEOs
- Longer time needed for scheduling



NEO Observations Annual Solicitation

- **Contained in annual omnibus Research Opportunities in Space and Earth Sciences (ROSES)**
  - Released February 18 this year (2014)
  - A component of Solar System Observations - Appendix C.6
  - See NSPIRES site:

    http://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={3EFFB689-0398-0F85-601A-65877CBCE61C}&path=open

- **NEO Observations – Important dates**
  - Step 1 Notices of Intent due April 7th
  - Proposals due June 6th
  - Peer Reviewed in August
  - Awards announced when FY2015 budget available to fund

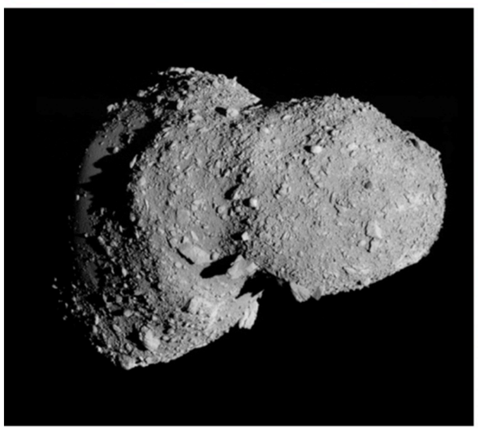
National Aeronautics and Space Administration

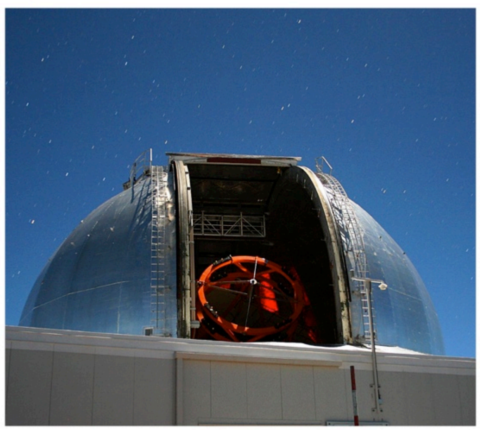
ARRM Reference Mission
AIOF Briefing 3/26/14

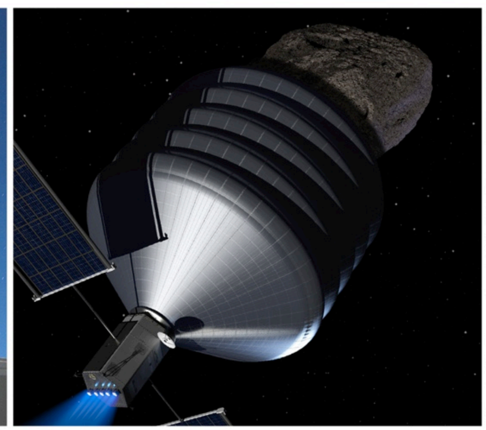
Brian Muirhead, JPL

Contributing NASA Centers:

JPL, GRC, JSC, LaRC, MSFC, KSC, GSFC



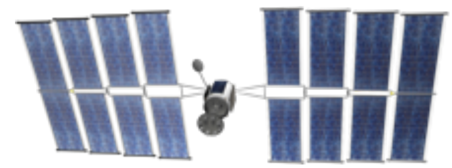




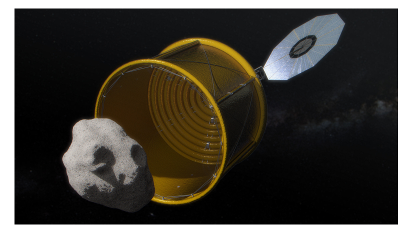
ARRM Reference Mission Primary Objectives

Architecture, mission design and flight system deliver the following primary mission functionality:

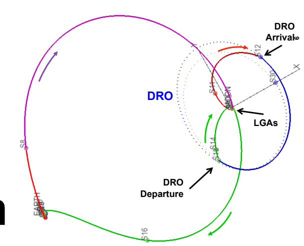
- High performance, high throughput, solar electric propulsion system with power up to 40 kW operating beyond Earth orbit. Applicable/extensible to expanding human exploration beyond LEO including higher power levels and use as a space tug



- Capability to rendezvous, characterize and operate in close proximity to a Near Earth Asteroid (NEA)
- Capability of capturing and controlling an asteroid up to the 10m mean diameter with a mass of up to 1000t



- Capable of accommodating a wide range of alternate capture and mission concepts (e.g. Phobos)
- Capability of maneuvering/control and returning a NEA, into a stable, crew accessible lunar orbit by the early-mid 2020's, and provide accommodations for crew to explore the NEA



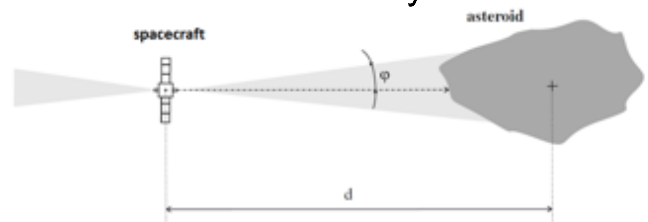
- Demonstrate lean development under a cost driven paradigm with acceptable technical and programmatic risk

ARRM Reference Mission Secondary Objectives

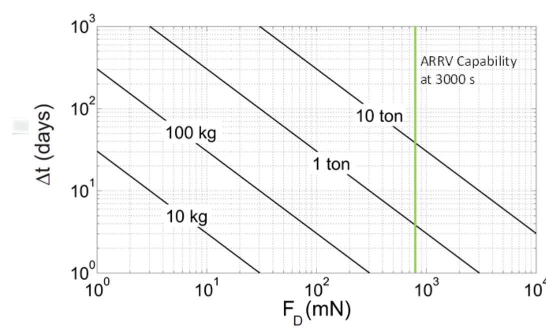
Architecture, mission design and flight system can deliver the following secondary objective functionality:

- **Planetary Defense (PD):**
  - Advanced SEP technology enables various PD strategies
  - Capability for Ion Beam Deflection or Gravity Tractor prox-ops and deflection within mission cost and timeline
- **Science: Provides a unique opportunity to understand the bulk composition and structure of a whole small NEA—a class of NEAs about which very little is known. The NEA could be any one of a wide range of asteroid types.**
- **Future Commercial Use:**
  - Demonstrates high-specific-power solar arrays and high-power SEP technology.
  - Demonstrates potential orbital debris removal technique via IBD on a *much larger mass*.
- **Future Resource Use: Demonstrates the ability to retrieve asteroid material mass much greater than the mass launched**
- **Partnership Opportunities (International and Commercial): Providing resources for contributed payloads or complementary missions**

IBD for Planetary Defense

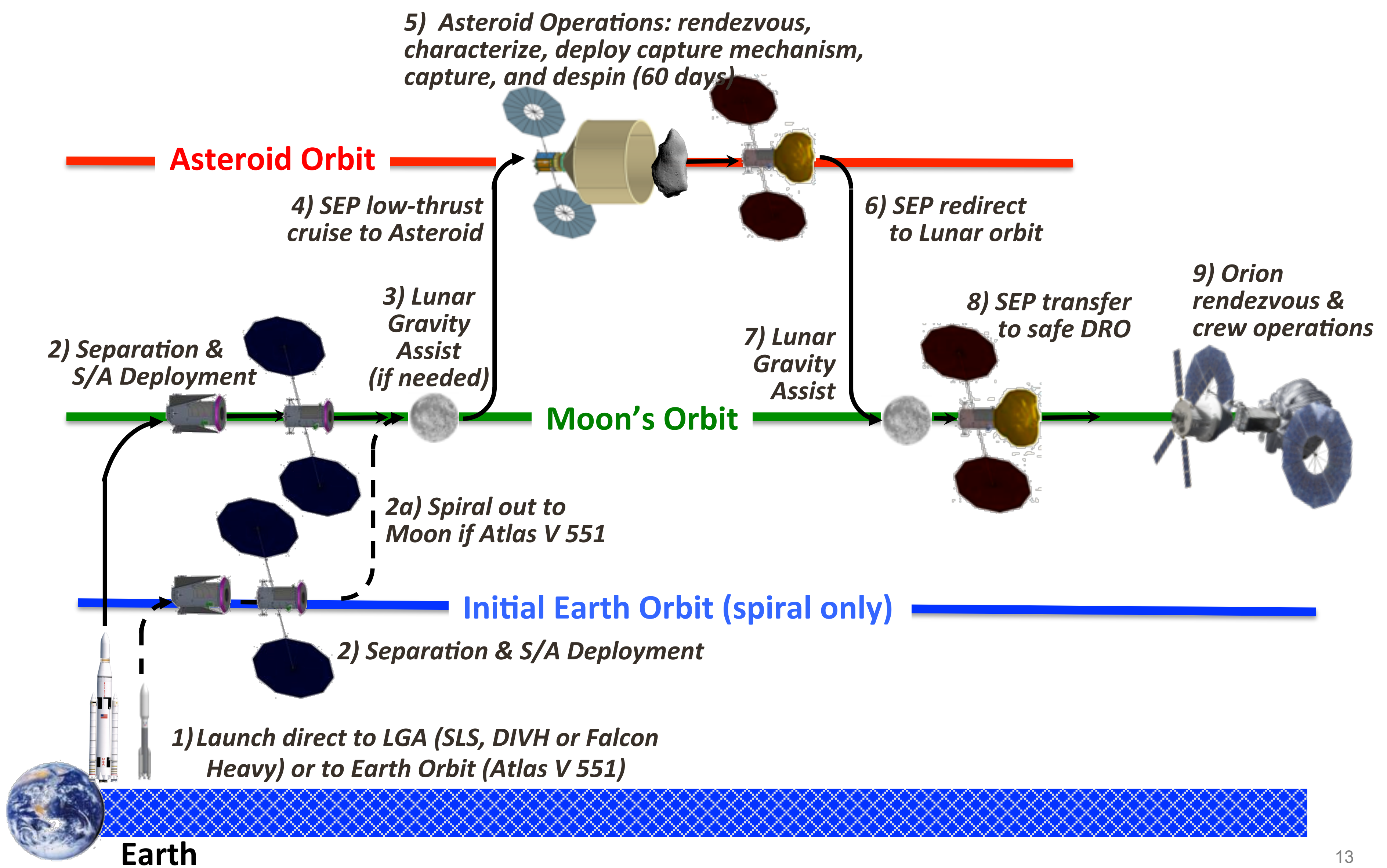


IBD for Orbital Debris Removal



Mario Merino, Eduardo Ahedo, Claudio Bombardelli, Hodei Urrutxua, and Jesus Peláez, "Ion Beam Shepherd Satellite for Space Debris Removal," 4th European Conference for Aerospace Sciences, July 2011

Mission Overview



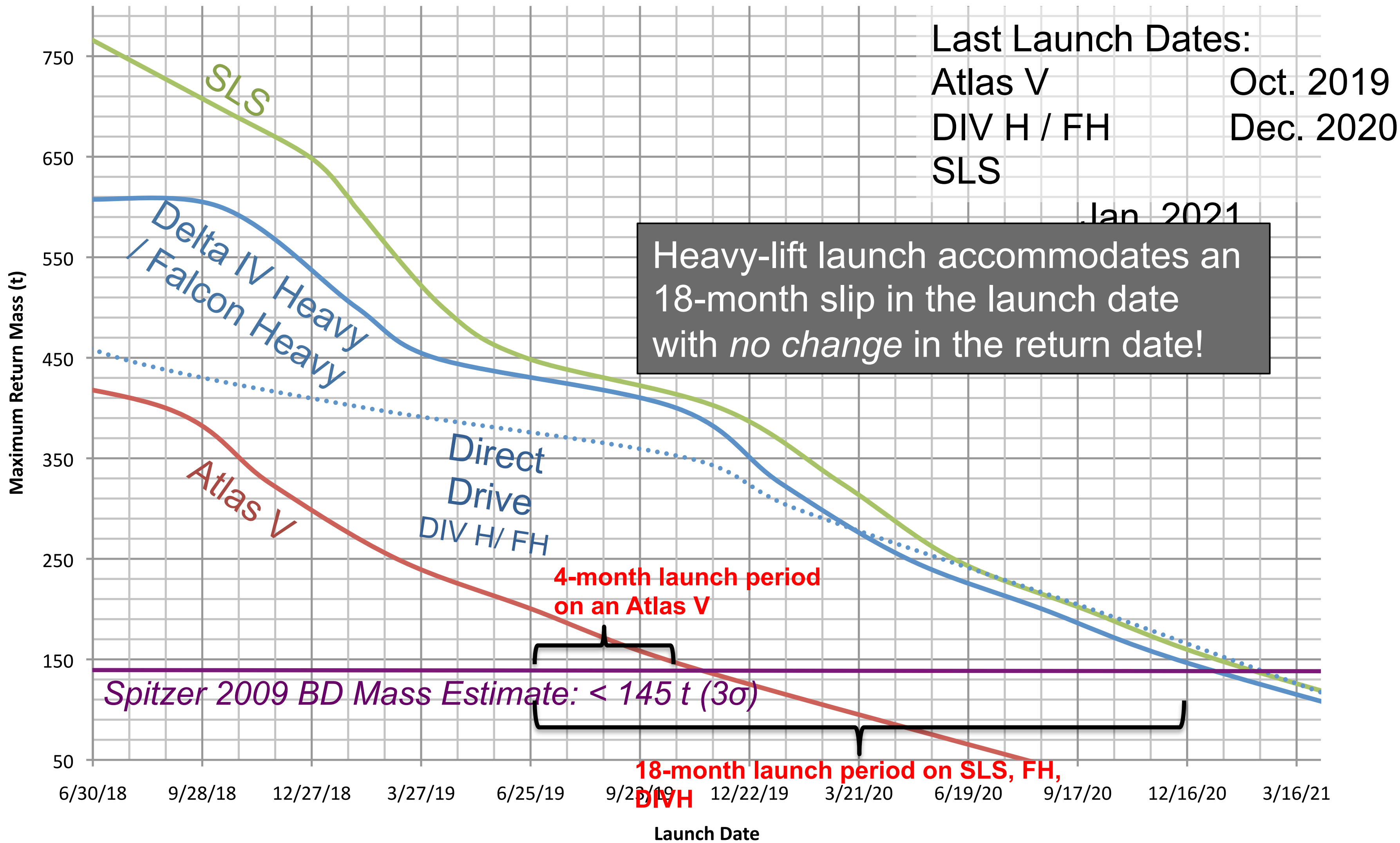
Candidate Asteroids for Mission Design

- **Each asteroid's return date is fixed & dictated by natural close approach times**
- **Lower V_∞ allows return of larger objects**
- **Assuming mid-2019 nominal launch**

Asteroid	Asteroid Mass Est.	Asteroid V-infinity	Earth Return Date	Crew Accessible	Notes
2009 BD*	30-145 t (returnable)	1.2 km/s	Jun 2023	Mar 2024 or earlier	Valid mission candidate, rotation period > 2 hrs, Spitzer-based upper bound on mass
2011 MD*	TBD (max 620 t)**	1.0 km/s	Jul 2024	Aug 2025	Spitzer obs. successful final characterization results pending Rotation period 0.2 hrs
2014 BA3	TBD (max 500 t)**	1.8 km/s	Jan 2024	Early 2025	Discovered Jan 2014, not detected by Radar Optical characterization pending
2013 EC20	4-43 t (returnable)	2.6 km/s	Sept 2024	Late 2025	Discovered March 2013, Radar characterized rotation period ~ 2 min 2024 return requires DIV H or FH launch 2020 return possible with Feb 2018 launch
2008 HU4	TBD (max 700 t)**	0.5 km/s	Apr 2026	Mid 2027	Close Earth flyby in April 2016

* High-fidelity trajectory analysis performed for 2009 BD and 2011 MD
** Max returnable mass using a Delta IV Heavy or Falcon Heavy

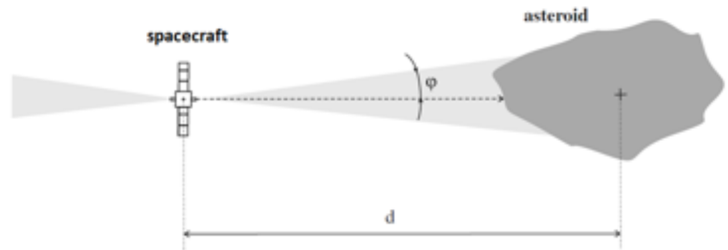
2009 BD: Max Return Mass vs. Launch Date



Planetary Defense (PD) Demonstration

- **ARRM could demonstrate the gradual, precise PD approaches of Ion Beam Deflection (IBD) or Gravity Tractor (GT) on a small or large asteroid**
- **For Reference Mission, a PD demo could be done with minimal impact to the mission design and operations**
  - No design changes, fits in existing timeline
  - IBD operations approach is independent of the size of the asteroid
- **IBD/GT relative performance on a small NEA**
  - IBD, <500 t (like 2009 BD) could impart: 1 mm/s in < 1 hour
  - GT, <500 t (like 2009 BD) could impart: 1 mm/s in < 30 hours

Ion Beam Deflector



Asteroid size-independent planetary defense demo

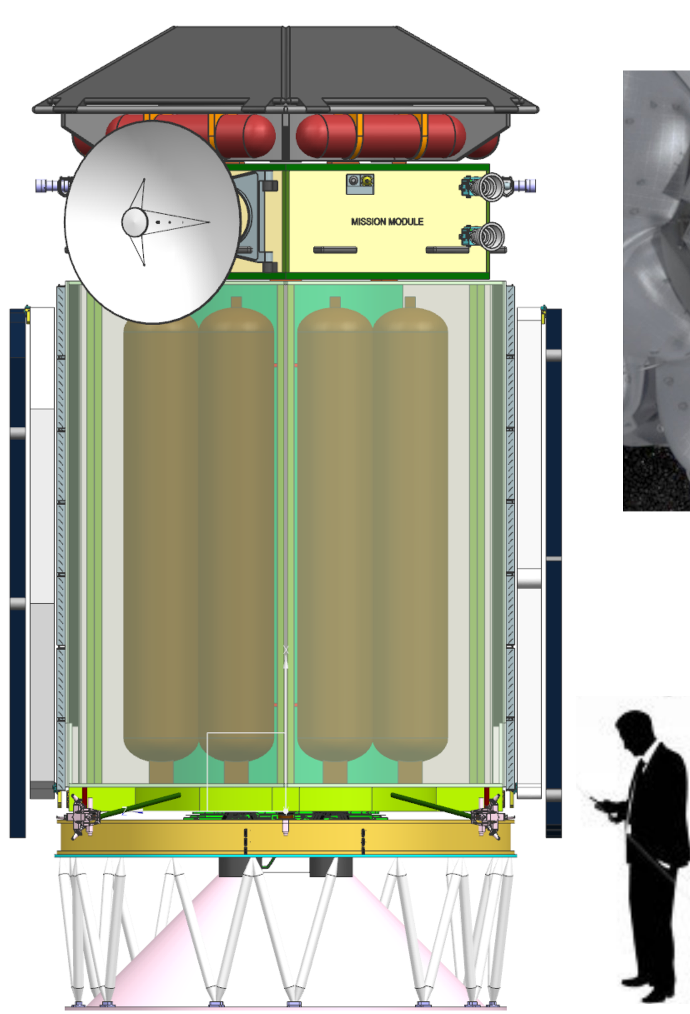
Asteroid Redirect Vehicle (ARV) Configuration – Key Features

Capture Mechanism
- Flight heritage instrumentation
- Inflatable capture bag

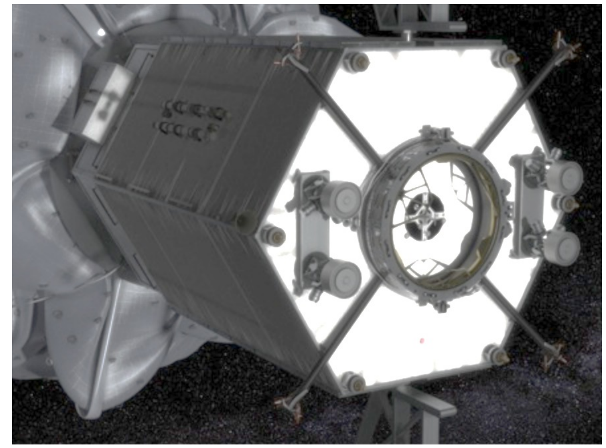
Mission Module
- Flight heritage avionics
- Simple Interface with SEPM

SEP Module
- Compatible with STMD solar array technology at 50 kW BOL
- EP derived from STMD Hall thruster/PPU technology
- Xe tanks seamless COPV with at least 10 t capacity
- Unique structure design
- Conventional thermal control
- Conventional reaction control subsystem

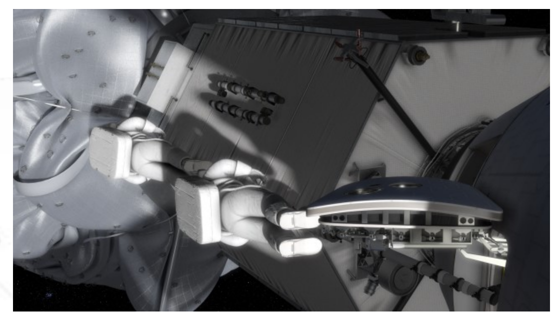
Launch Vehicle I/F
- Compatible with 5m fairings
- Unique adapter depending on LV selected



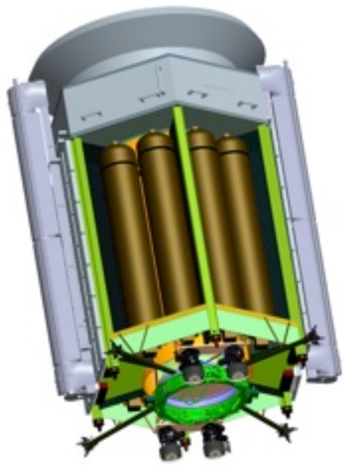
Orion docking I/F

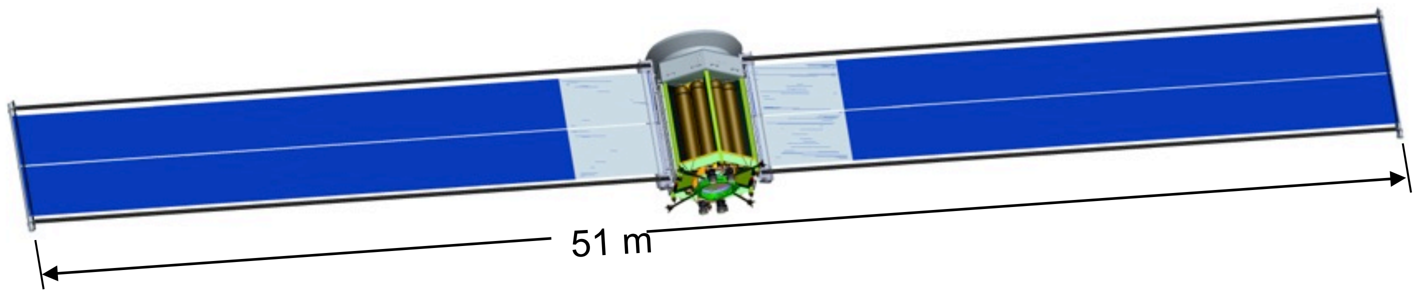


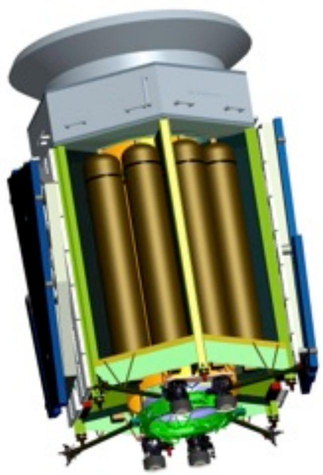
Crew access path

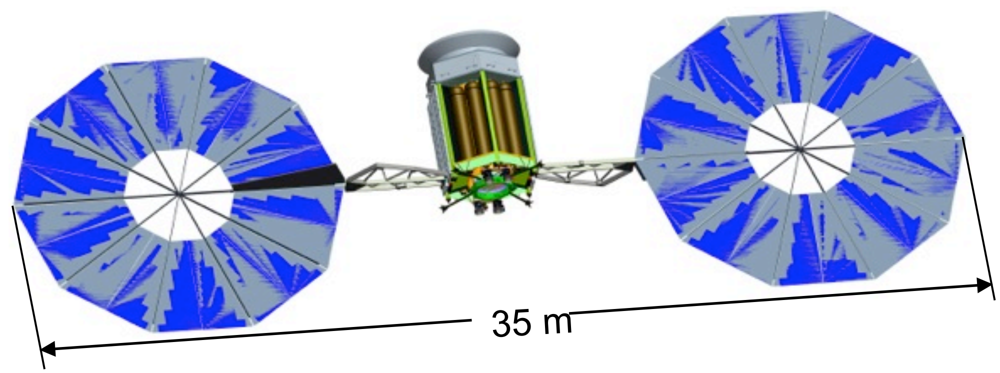


Representative Flight System Deployed Configurations









The Target and the Bag

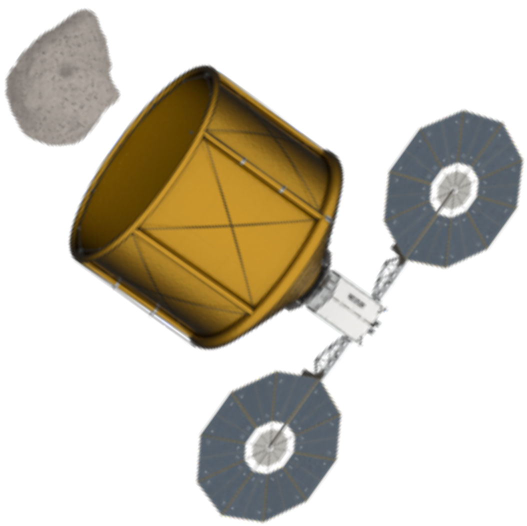
- **Most large asteroids are believed to be loosely held together bodies, i.e. rubble piles. The likelihood that small bodies are fragments of large bodies implies the need for containment in a bag.**
  - Tolerant of a wide range of asteroid shapes and mechanical properties
  - Assures containment and eliminates dust as hazard for S/C
  - Local forces on asteroid due to capturing, cinching, berthing and maneuvering are estimated to be small compared to the strength of the body
- **Based on inputs from the EVA office and the strong desire to minimize complexity and risk we have limited the design space to simple spinners or slow, <0.5 rpm, tumblers, estimated to include 75% of the small asteroid population**

Rubble Pile Compressive Strength

- Bolide Record: 0.1- 1.0 MPa (15-150 psi)
- “Dirt” Clod: .2-.4 MPa (30-60 psi)
- Possible lower strength <0.1MPa

Possible Spin States

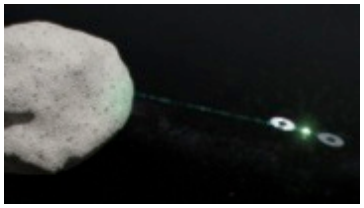
- Slow (<0.5 RPM), Simple Spin
- Slow (<0.5 RPM), Tumbling
- Fast (~<2 RPM), Simple Spin
- Fast (~<2 RPM), Tumbling



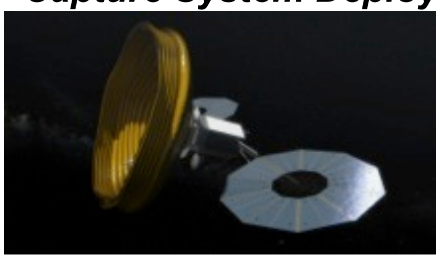
Rendezvous and Proximity Operations

Orbit Refinement and Rendezvous
(Radio and Optical)

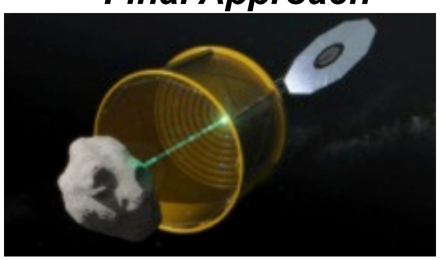
Characterization



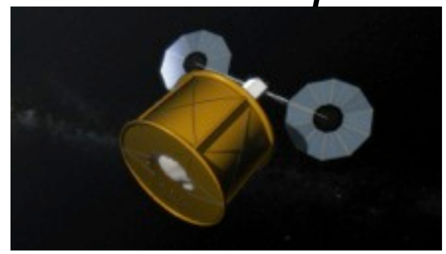
Pre-Capture
Capture System Deploy



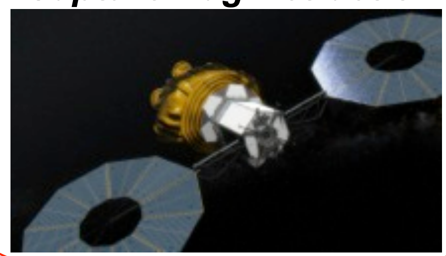
Final Approach



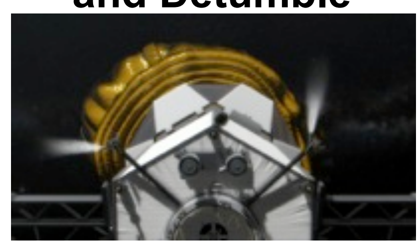
Capture
Mechanical Capture



Capture Bag Retraction

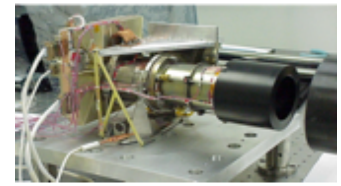


Characterize, Spin down, and Detumble

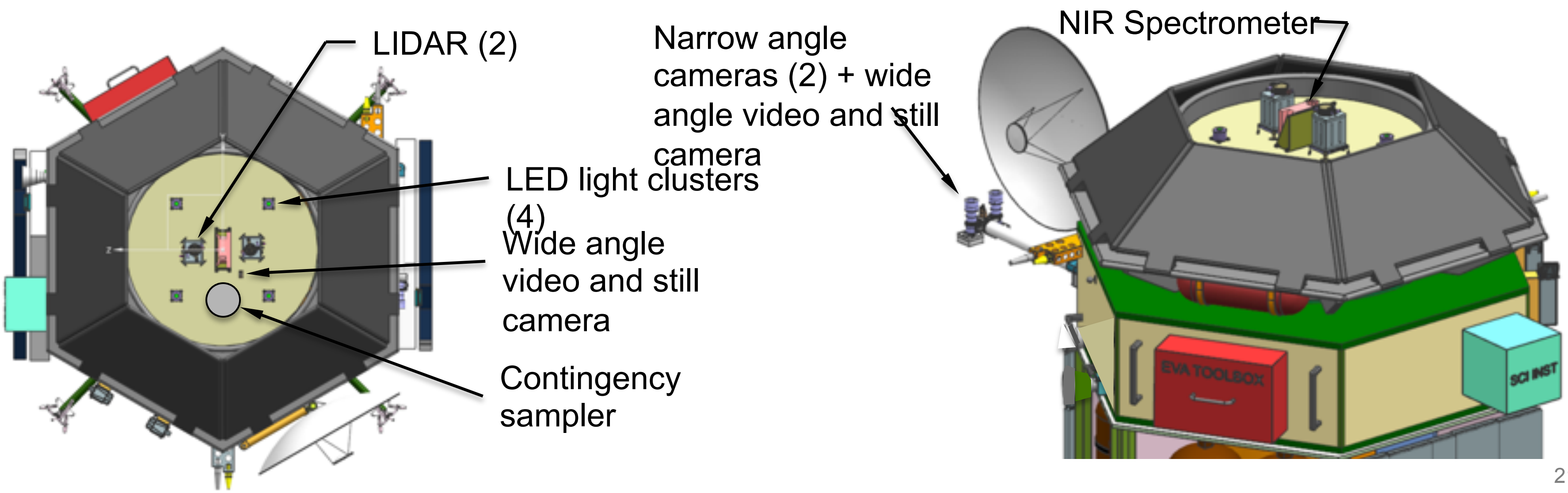


Asteroid Rendezvous & Prox-Ops Sensors

- **Defined minimum sensor suite with simplest control strategy to minimize complexity and cost (consistent with AR&D study conclusions)**
  - Narrow Angle Camera (NAC, 1.4 degree FOV) (2) used for both optical navigation and, at a range > 1km for mapping, generating shape model (including rotation/dynamics and inertia properties)
  - Scanning LIDARs (2, 60 degree FOV): at <2 km, for mapping, updating shape model and closed loop control
  - Wide angle cameras and lights (e.g. RocketCams) for additional information and outreach (could be HD quality)



- **Near IR spectrometer for surface composition (not in control loop)**



National Aeronautics and Space Administration

Asteroid Initiative Opportunities Forum

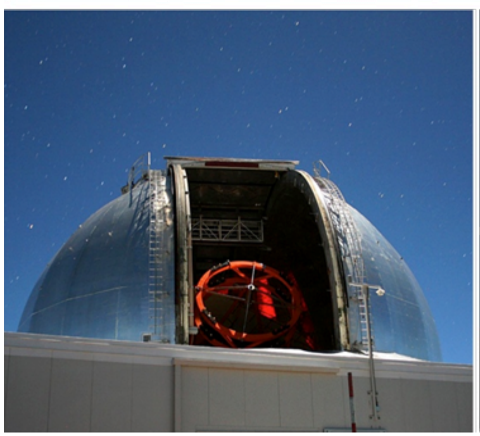
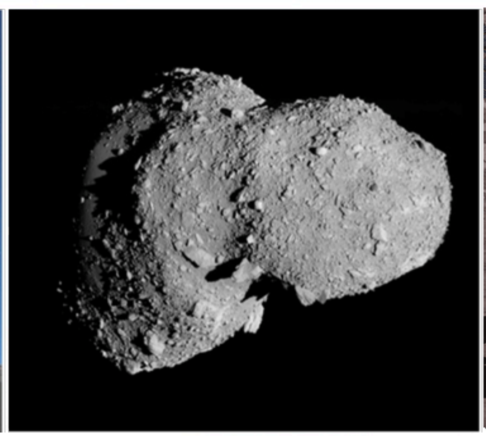
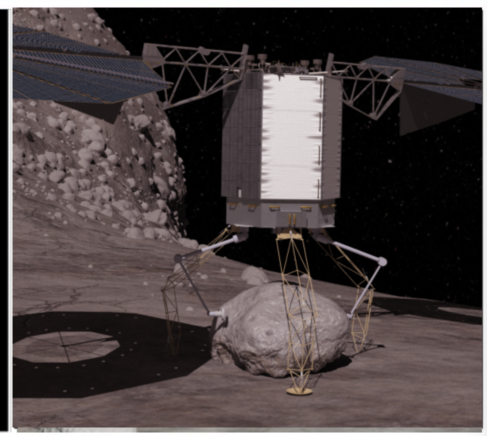
ARRM Robotic Boulder Capture Option

March 26, 2014

Dan Mazanek, LaRC

Contributing NASA Centers & Academia:

GSFC, ARC, GRC, JPL, KSC, MSFC, U. Colorado Boulder, U. Alaska Fairbanks

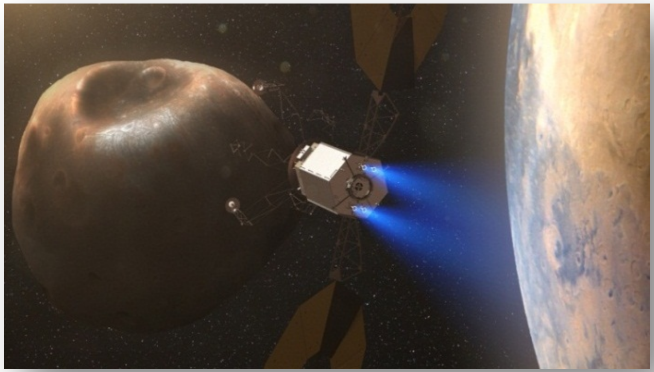




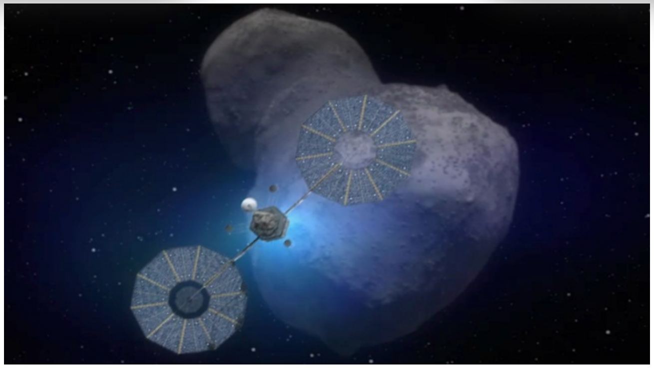

Mission Overview

Utilizes a risk-informed design strategy to develop a mission that meets the following primary objectives.

Return a boulder from the surface of a large near-Earth asteroid (NEA) to a stable lunar orbit.

Mature key technologies and operations in human-class Mars mission environment.





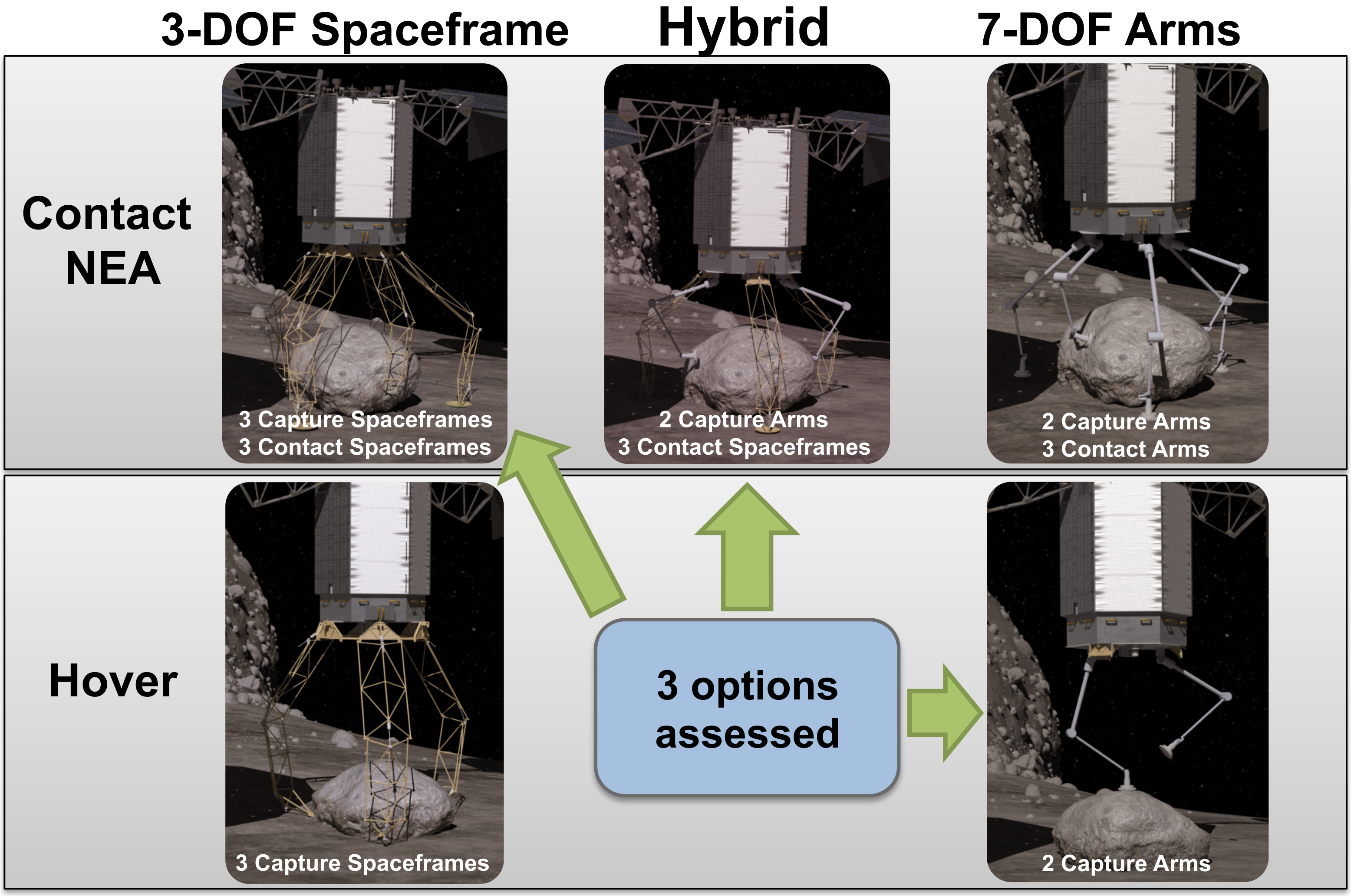
Alter the trajectory of an asteroid of potentially hazardous size (~100+ m diameter).

Mission Overview Video

Watch the animation at:

http://youtu.be/DWATKE7VxTc

Proximity Operations and Capture System Options

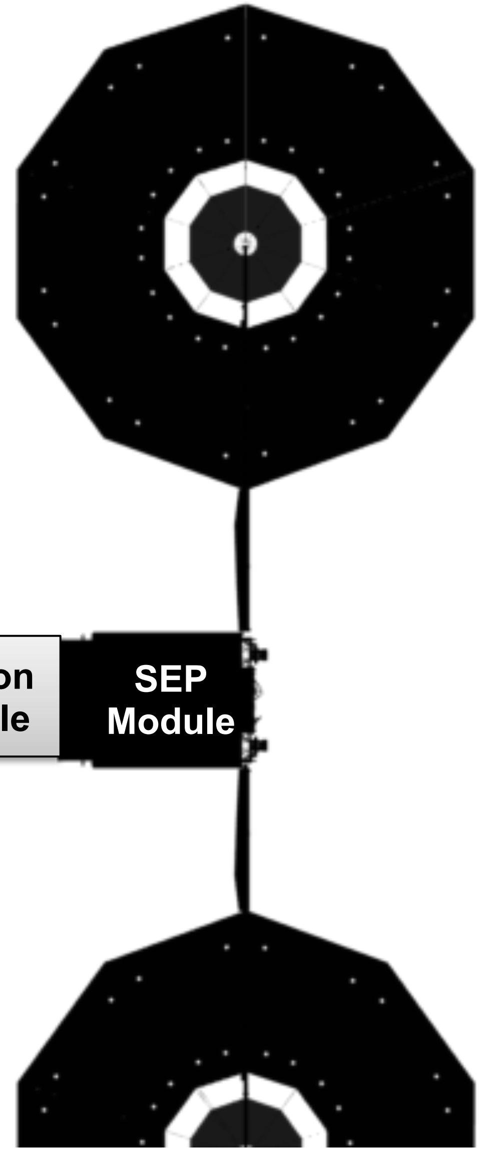


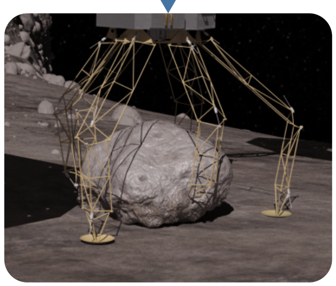
Payload Module Approach

- Allows integration and functional testing of entire capture system (mechanism, avionics, sensors, software) prior to system integration.
- Streamlines the interface between the capture system and the mission module, but increases management and systems engineering.
- Promotes reuse of SEP & Mission Module designs with minimal changes as the Payload Module contains the majority of the mission-specific hardware.

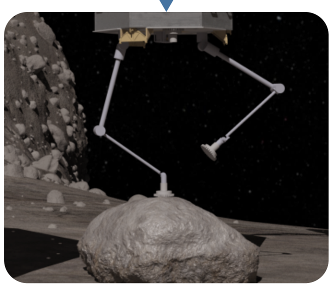
Capture and Proximity Ops Payload Module ⇔ **Common Interface** ⇔ **Mission Module**

Unconditioned Power, Data, Thermal

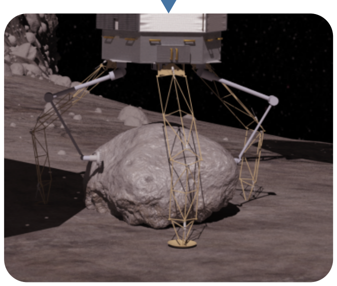




Spaceframe



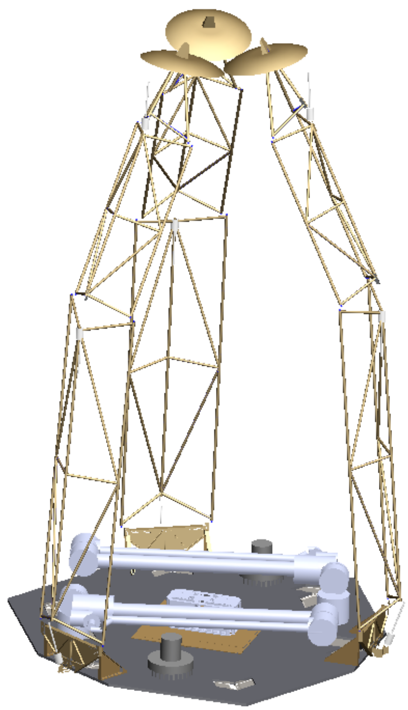
7-DOF Arms



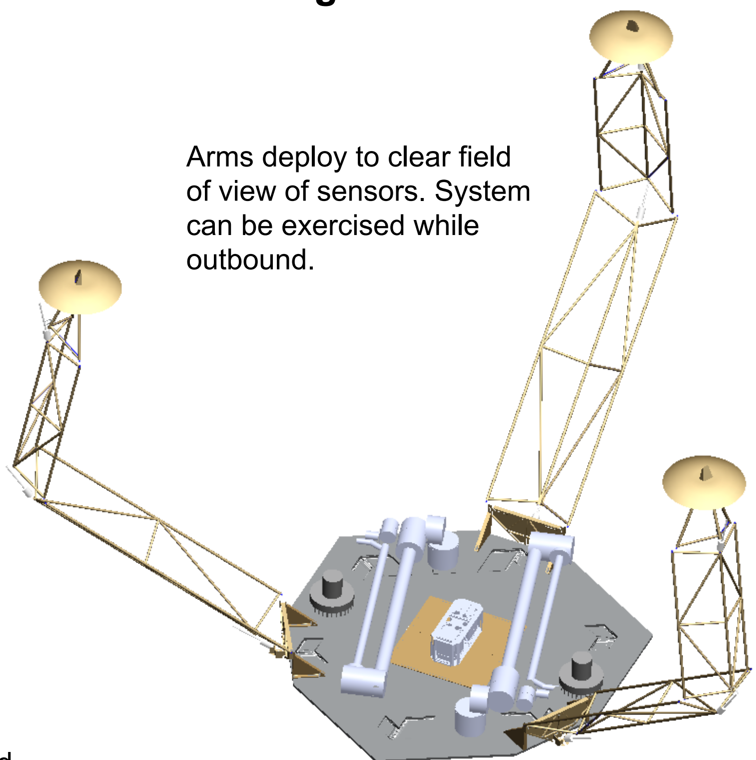
Hybrid

Hybrid Option Design

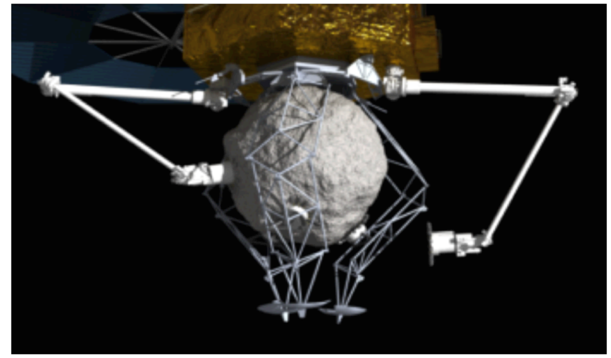
- **7-DOF Arms and microspine grippers are built and tested in parallel to Spaceframe contact arms**
- **Assembles as single module for integration with the S/C bus**



Contact Arms pinned at pads and
7 DOF arms pinned to deck for launch.



Arms deploy to clear field of view of sensors. System can be exercised while outbound.



Contact Arms with Sample Collectors and boulder constraint after capture.

Testing of microspine gripper prototype

Hybrid capture system optimizes functionality and maximizes extensibility of concept.

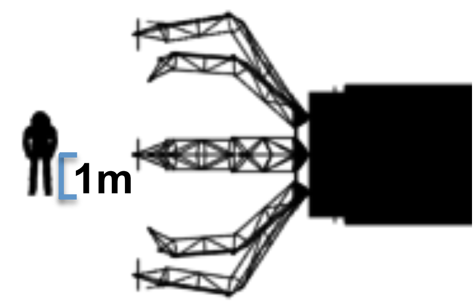
Boulder Mass and Size and Density

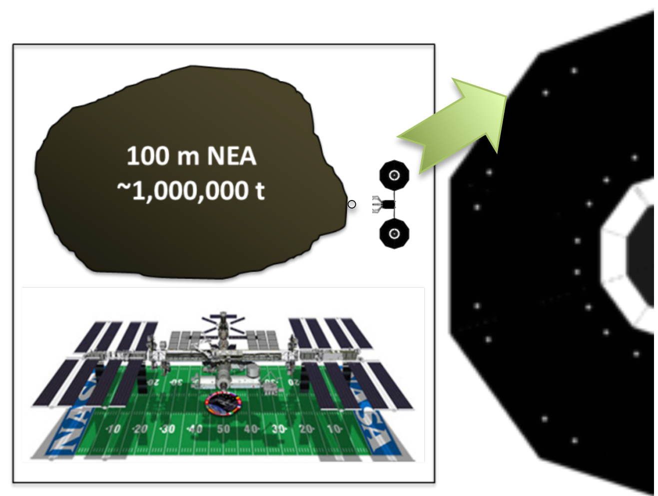
NEA Type

Mass (t)	Metallic 5.2 g/cm^3	Stony 3.22 g/cm^3	Carbonaceous 1.62 g/cm^3
1	0.7 m	0.8 m	1.1 m
10	1.5 m	1.8 m	2.3 m
20	1.9 m	2.3 m	2.9 m
30	2.2 m	2.6 m	3.3 m
40	2.5 m	2.9 m	3.6 m
50	2.6 m	3.1 m	3.9 m

Note: Assumes spherical extent

Observed size is a key characteristic of the object returned.





Candidate Target Boulder Return Sizes

Launch no earlier than June 2019

Crew Availability in stable LDRO in February - May of:

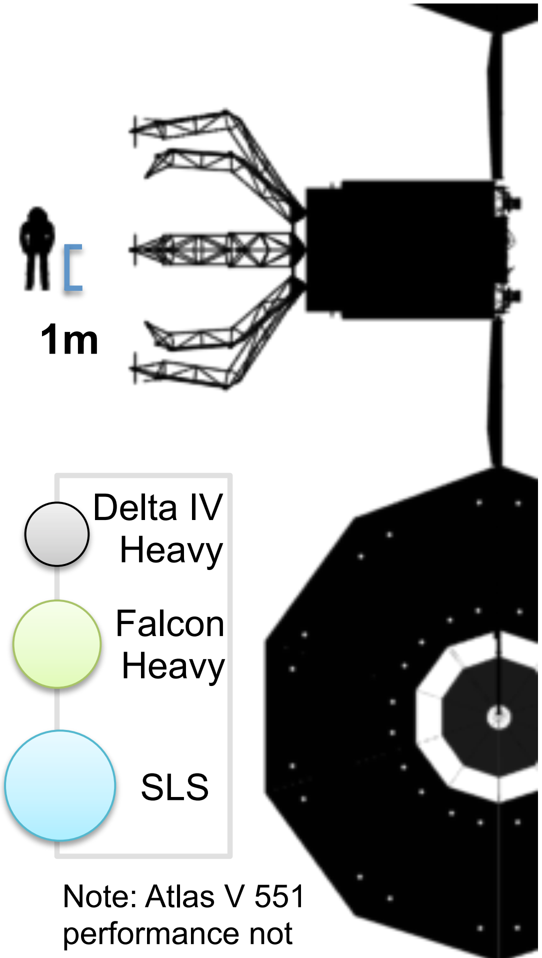
Target	Density	2024	2025	2026	2027
Itokawa	~3.22 g/cm^3	0.8	1.3, 1.4, 1.6	2.2, 2.3, 2.8	2.2, 2.3, 3.0
Bennu	~1.62 g/cm^3	1.7, 2.0, 2.0	2.3, 2.4, 3.0	3.0, 3.0, 3.5	3.0, 3.2, 3.6
1999 JU_3	~1.62 g/cm^3	0.6, 1, 1.3	2.4, 2.5, 2.8	3.3, 3.3, 3.5	3.5, 3.8, 3.9
2008 EV_5	~1.62 g/cm^3	2.0, 2.3, 2.4	3.3, 3.4, 3.8	3.6, 3.6, 3.8	3.8, 3.9, 4.1

Size (m)

Delta IV Heavy

Falcon Heavy

SLS



Note: Atlas V 551 performance not assessed.

Robotic Boulder Capture Option has a set of candidates that are robust to changes in return dates.

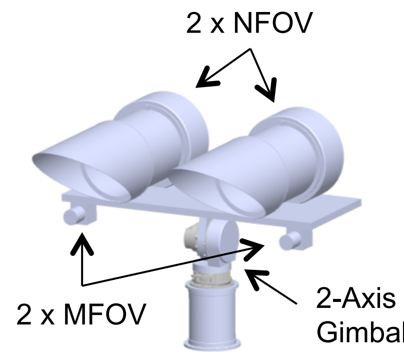
Masses and additional data for June 2020 and June 2021 launches in backup

Sensor Selection

Sensor Suite

- **Narrow FOV Camera**
- **Medium FOV Camera**
- **Wide FOV Camera**
- **3D LIDAR**
- **Situational Awareness Cameras**

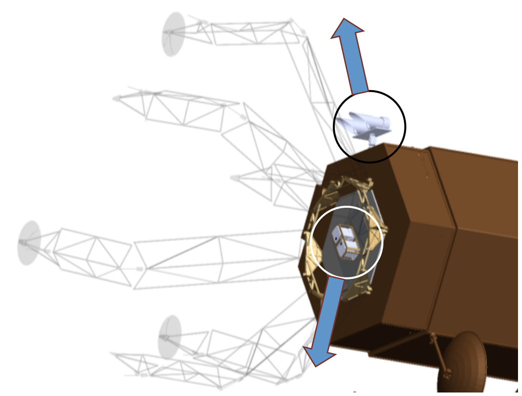
The use of multiple redundant systems enable identification and characterization of thousands of boulders in the returnable mass range, long-/close-range navigation, and execution of autonomous capture ops.

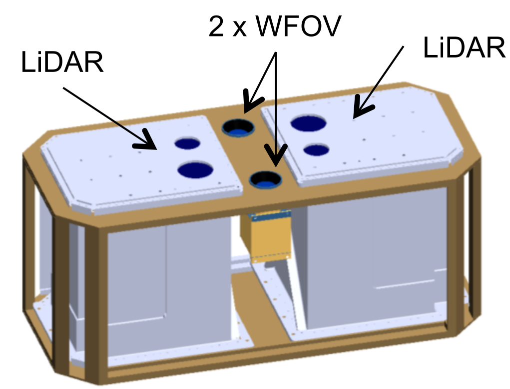


Extensibility Benefits

- Validation of optical nav techniques (Exploration).
- Video of ops for Exploration, Public Engagement, Science.
- Enhanced surface coverage, detailed internal structure (Science, Exploration).

Long characterization and imaging phases collect data to meet mission needs and provides value for science, public engagement, and future exploration activities.





Ground Penetrating Radar

- Not required to characterize boulders.
- Provides further risk reduction through sub-surface imaging.
- Has extensibility value to both science and exploration.

Ideal Mission of Opportunity

Planetary Defense Demonstration at a Larger NEA

Planetary Defense Options	Capable?
Kinetic Impactor	✓
Enhanced Gravity Tractor (EGT)	✓
Gravity Tractor	✓
Ion Beam Deflection (IBD)	✓

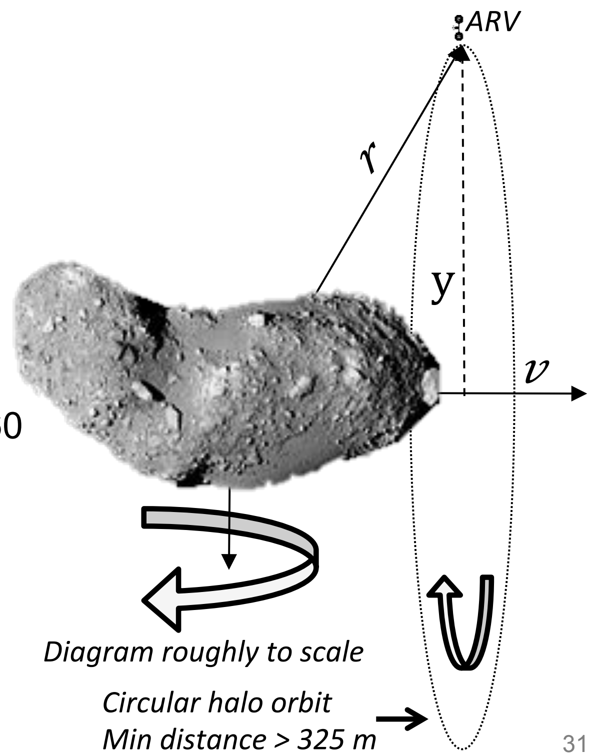
Selected Enhanced Gravity Tractor for Itokawa Case Study

- Relevant to potentially-hazardous-size NEAs: efficiency increases as boulder and NEA masses increase.
- Leverages collected boulder mass.
- Allows spacecraft to maintain safe, constant distance from NEA.
- Demonstrates sustained operations in asteroid proximity.

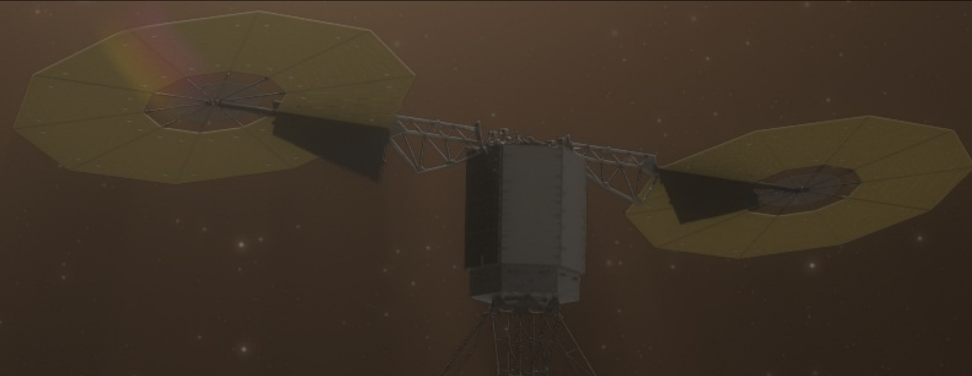
Focus is on demonstrating the applicability of Enhanced Gravity Tractor on potentially-hazardous-size NEA.

Enhanced Gravity Tractor Concept of Operations for Itokawa

- Phase 1: Fly in close formation with the asteroid with collected boulder (60 days required for measurable deflection with 120 days of reserve performance).
- Phase 2: Wait for orbital alignment to become favorable to allow measurement of deflection beyond 3-σ uncertainty (~8 months from start of Phase 1).



Closing Remarks



The robotic boulder capture option addresses the needs of a broad set of stakeholders, and leverages precursor missions and existing agency capabilities to ensure mission success.

- **Mars-Forward Human Exploration and Extensibility**
- **Planetary Defense on Hazardous-size NEA**
- **Science with Community Collaboration**
- **Commercial & International Opportunities**

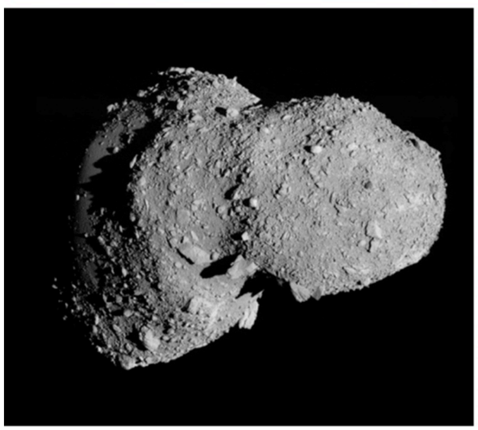
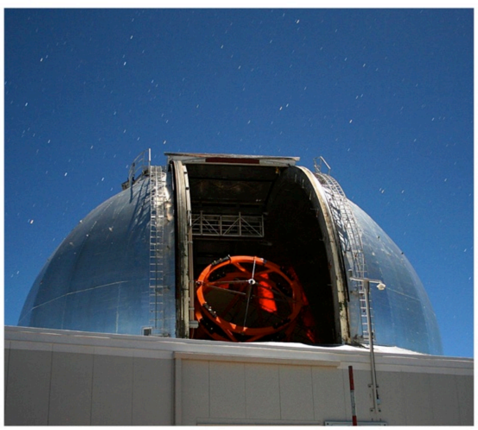
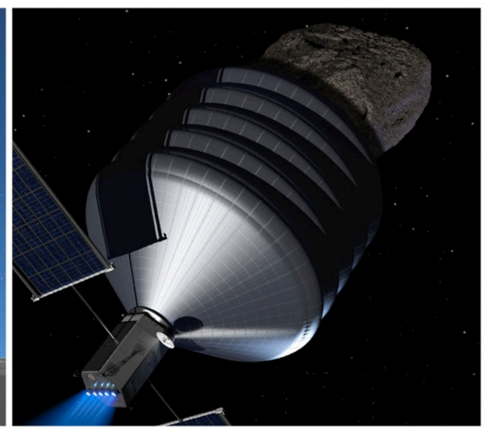
Thank you for your time and attention.

National Aeronautics and Space Administration

Asteroid Initiative Opportunities Forum
Robotic Concept Integration

Jim Reuter

March 26, 2014


Robotic Concept Integration Team

Purpose:

- **Assess the ARM robotic concepts and provide a recommended path forward.**

Membership:

- **Chair**
- **Leads from each Study Team**
  - Identify Segment
  - Robotic Concept Leads
  - Crewed Mission Segment
- **Additional members from across the Agency**

Schedule:

➢ **October 24, 2013**	**Kickoff**
➢ **December 17, 2013**	**Status**
➢ **February 19, 2014**	**Findings**

Additional Special Study Advisory Teams:

- Automated Rendezvous and Docking (AR&D) Commonality Team
- Curation and Planning Team for Extraterrestrial Materials (CAPTEM)
- Capture System and Proximity Operations Peer Review Team
- Independent Cost "Sanity Check"
- Small Bodies Assessment Group Special Action Team (SBAG SAT)
- Planetary Defense Experts

Robotic Concept Trade Study Figures of Merit (FOMs)

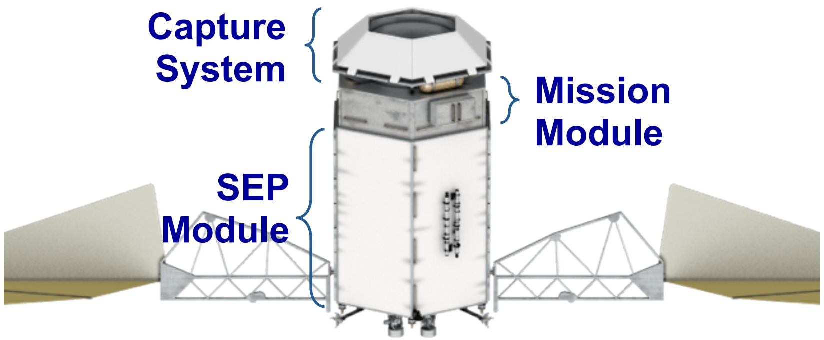
- **Cost**
- **Schedule**
- **Primary Objectives**
  - Support of Human Exploration (1)
  - Technology Demonstration (2)
  - Enhanced Observation Campaign
- **Secondary Objectives**
  - Planetary Defense Demonstration
  - Science
  - Commercial and Resource Use
  - Partnership Opportunities
- **Safety & Mission Success**
  - Crew Safety
  - Mission Success/ Technical Risk
- **Sustainability**
  - Stakeholder Interest
  - Mission Extensibility

(1) Human exploration to an asteroid in the mid-2020's that prepares for future exploration.

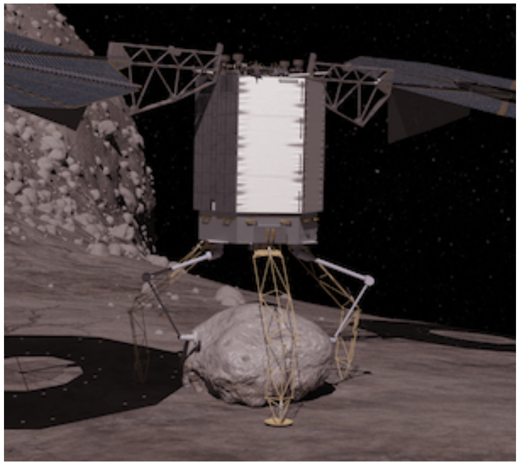
(2) Enable deep-space human exploration with applications for the nation's aerospace community; advanced solar electric propulsion.

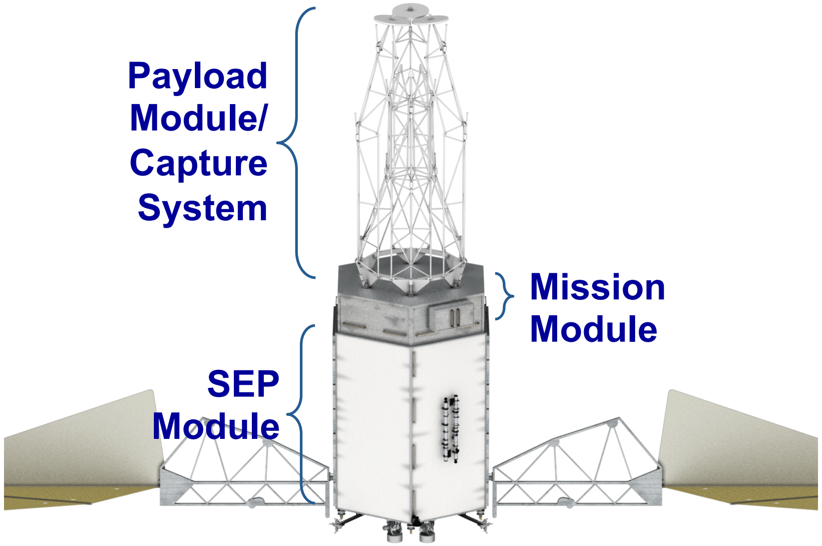
Asteroid Redirect Mission Robotic Concepts

Small Asteroid Capture

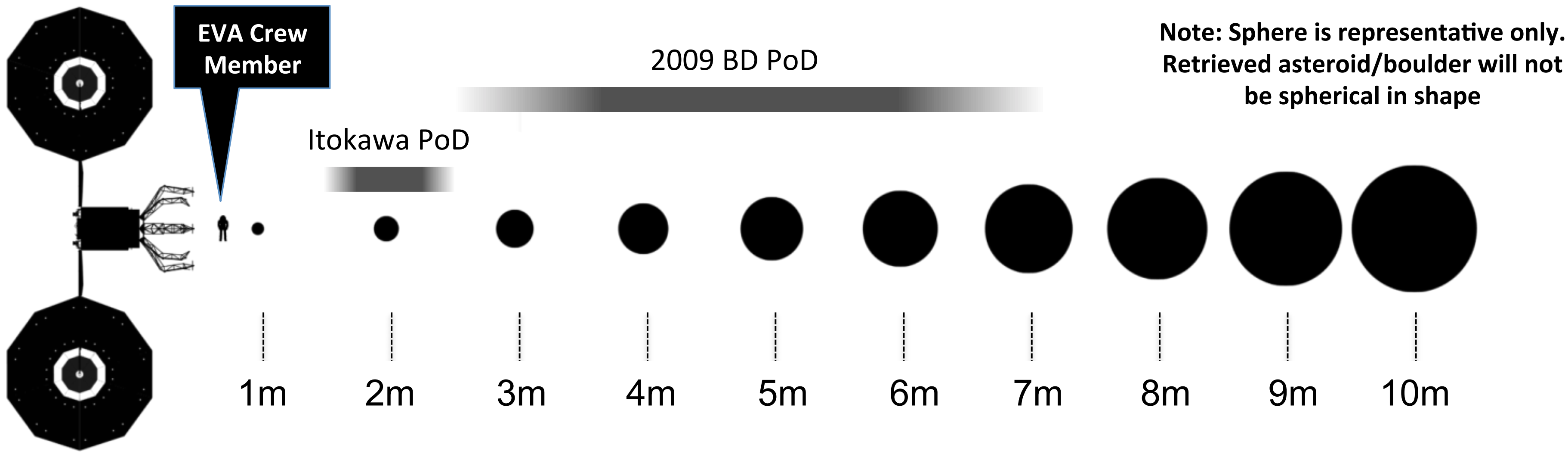


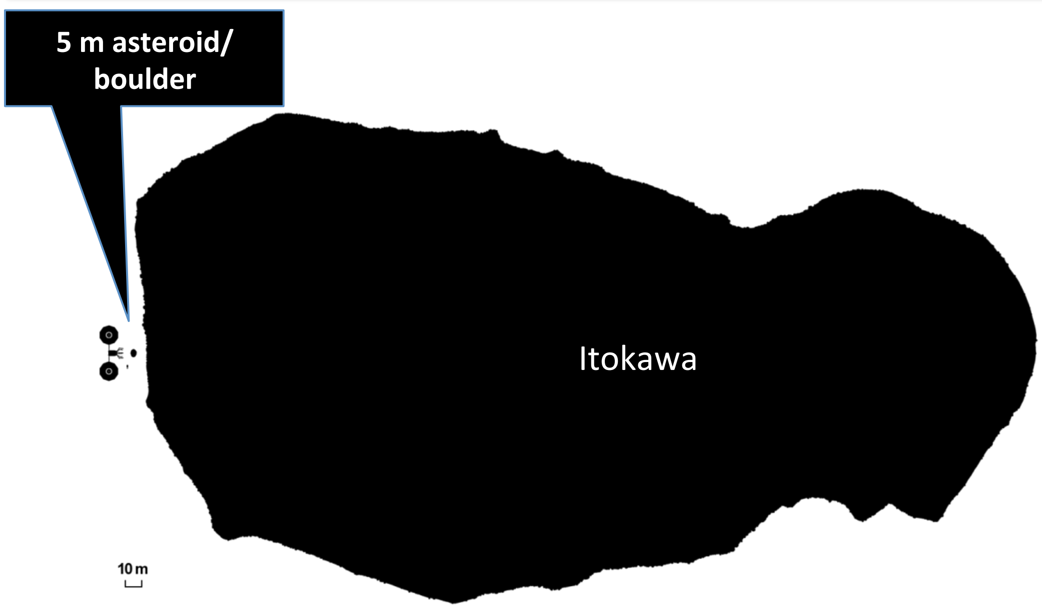
Robotic Boulder Capture

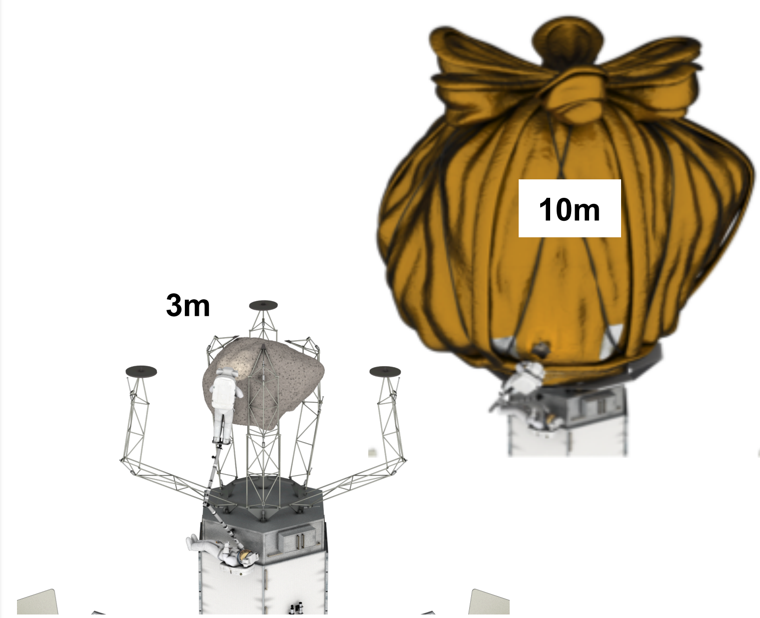




Size Comparisons

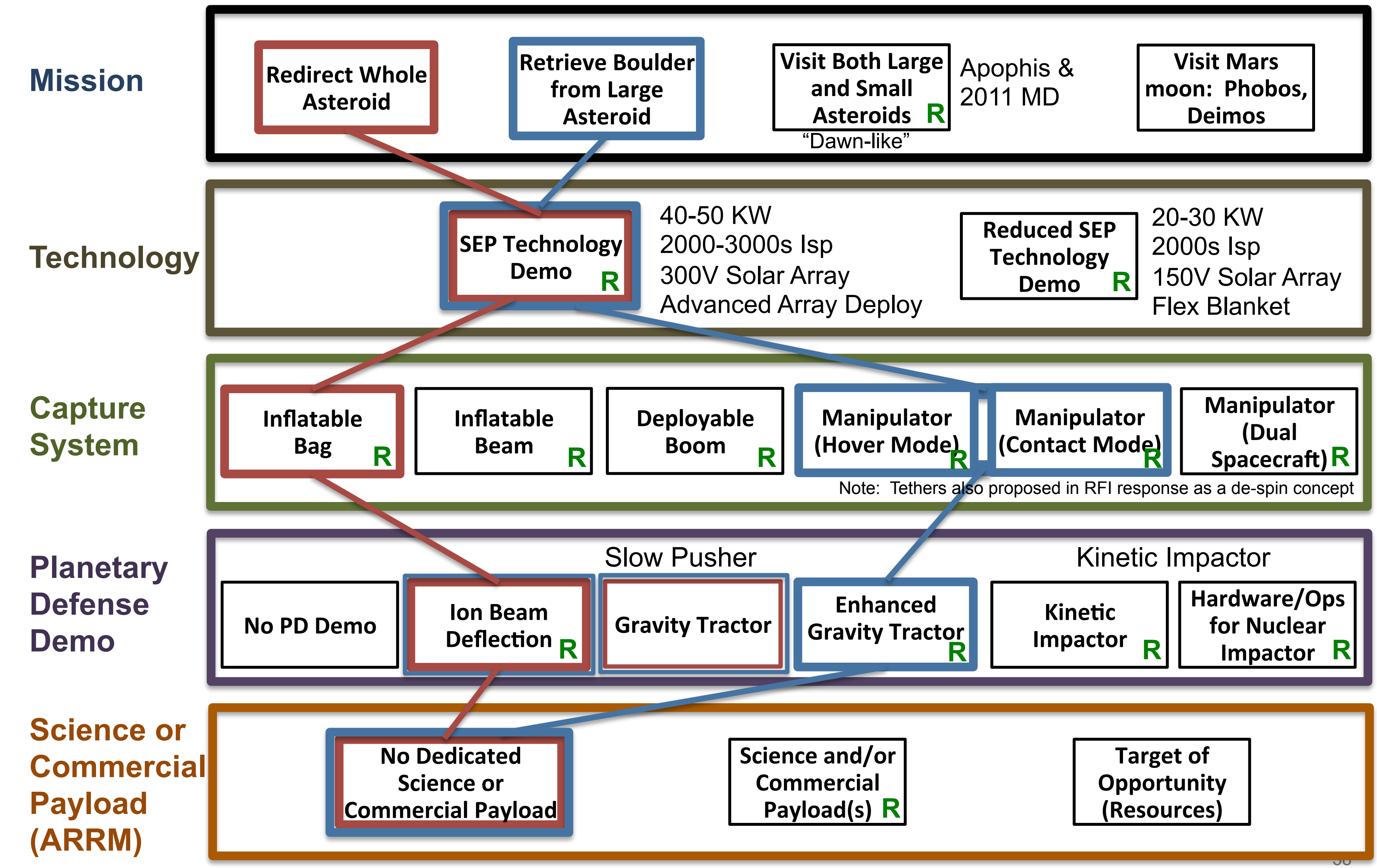






Robotic Concept Trade Space

Small Asteroid Capture PoD
Robotic Boulder Capture PoD



R = Received RFI Unique Inputs

Note: Slow Pushers could work for either concept

Mission Profile Comparison – Points of Departure

Phase/Activity	Small Asteroid (2009 BD)		Robotic Boulder (Itokawa)	
	Date/Duration	Xenon Use	Date/Duration	Xenon Use
Launch	**June 1, 2019**		**June 20, 2019**	
Outbound Leg	1.4 years	899 kg	2.2 years	4,020 kg
Asteroid Rendezvous & Proximity Ops				
Arrival	**Jan. 3, 2021**		**Sept. 11, 2021**	
Characterization & Capture	30 days		51 days	
Capture Phase Margin	30 days		18 days	
Planetary Defense Demo	1 hour		262 days	170 kg
Margin (Missed Thrust, Prox Ops)	30 days		69 days	30 kg
Departure	**Apr. 3, 2021**		**Oct. 16, 2022**	
Inbound Leg	2.2 years	858 kg	2.5 years	1,830 kg
Earth-Moon System DRO Insertion	Feb 15, 2024	127 kg	August 2025	70 kg (TBR)
Earliest ARCM Availability	**Feb-May 2024**		**Aug-Sept. 2025**	

Assumes Heavy Lift Launch Vehicle (Delta IV Heavy/Falcon Heavy) for PoD. SLS would improve performance.

Xe used: 1,884 kg
SEP Operating Time: 400 days
Asteroid Return Mass: 30-145t (2.6-7m mean diameter)

Xe used: 6,230 kg
SEP Operating Time: TBD days
Boulder Return Mass: 11 t (1.8 m spherical, 2.3 m max extent*)

* At 2,2,1 aspect ratio

Special Study Team Results

Study Team	Results
Automated Rendezvous & Docking (AR&D) Commonality Team (Multi-center NASA team)	• Identified a viable common AR&D sensor suite applicable to both concepts and crewed mission
Curation and Planning Team for Extraterrestrial Materials (CAPTEM) (Joint University and NASA team)	• 11 findings provided to guide EVA objectives for the crewed mission and support assessment of concepts.
Capture System and Proximity Operations Peer Review Team (NASA team)	• Overall technical & schedule risk assessed for each concept.
Independent Cost "Sanity Check" (NASA team)	• Performed "sanity check" of the basis of estimate for each concept
Small Bodies Assessment Group Special Action Team (Joint University and NASA team)	• Provided information on the physical nature of small asteroids and boulders. • Forward work to provide science considerations.
Planetary Defense Experts (University and NASA)	• Provided perspectives related to potential for ARM planetary defense technique demonstrations

RCIT Risk Assessment

- **104 risks captured; 19 key risks**
- **Assessed risks before and after mitigation; expected complexity and urgency of mitigation tasks**
- **Key Small Asteroid Capture Risks:**
  - Target availability
  - Inflatable capture system packaging, deployment, & materials development
  - Inflatable capture system management during deploy, cinching & asteroid positioning
  - Crew situational awareness during EVA
- **Key Robotic Boulder Capture Risks:**
  - Asteroid proximity operations and boulder capture including fault management logic for multiple attempts
  - Debris mitigation for capture system and spacecraft
  - Capture system launch configuration & deployment
  - Boulder structural integrity, retention forces
- **Key Common Risks:**
  - Solar Electric Propulsion technology and 300-V power system development

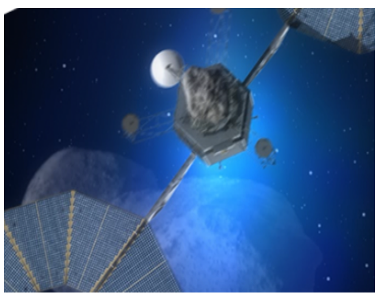
No risk show-stoppers found

Secondary Objectives and Extensibility

Planetary Defense

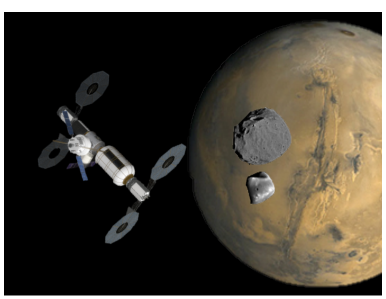
Small Asteroid Capture	Robotic Boulder Capture
• ARM prox ops, autonomous ops, characterization & algorithms applicable • Slow Push techniques implemented with small development costs	
• Slow Push techniques (IBD, GT) demonstrated much more quickly	• More relevant on a PHA • Opportunity for kinetic impactor

Science, Commercial and Resource Use



Small Asteroid Capture	Robotic Boulder Capture
• Applicability of high power SEP, ARM engineering instruments • Potential to host "target of opportunity" payloads	
• Opportunity to learn about <10m asteroids; ~1:10 are C-type	• Better opportunity to return desired material (if C-type) w/geologic context

Extensibility



Small Asteroid Capture	Robotic Boulder Capture
• In-space SEP and prox ops w/uncooperative target provides broad opportunities (human exploration, science, commercial) • Supports Exploration Roadmap with partnership opportunities – **Mars Forward**	
• Inflatable technology uses • Ion Beam Deflection for orbital debris	• Near surface ops; remote manipulator and gripper concepts applicability

Robotic Concepts Summary
Key Distinguishing Characteristics

Small Asteroid Capture Concept

+ Capture and control of a complete asteroid
+ Capture system accommodates asteroid structural uncertainty
+ Likely lower cost/cost risk

– Current uncertainty in selectable target
– Uncertainties in flex/control system interactions of inflatable structure could drive test and analysis plans
  – Would be mitigated by eliminating low probability cases of high speed tumblers

Robotic Boulder Capture Concept

+ Selectable asteroid target assured
+ More flexibility to launch date changes
+ Flexibility in boulder selection
+ Improved mission extensibility
+ Easier to provide EVA crew situational awareness
+ Better opportunity to return preferred asteroidal material (C-type)

– Reliance on boulder structural integrity
  - Mitigated by multiple attempt capability
– Increased operations and fault management complexities including multiple capture attempts
– Increased concern over accommodating launch/EVA loads
  - Needs assessment

Both Concepts are Viable with No Technical Showstoppers

Findings From the Asteroid Initiative Workshop

Asteroid Capture Systems

- ✔ Conduct **trade between deployable booms and inflatable beams** with respect to the reference capture system concept.
- ✔ Investigate cost effective ways to **de-tumble the asteroid prior to capture** to make it a more cooperative target, such as using **tethers** for momentum transfer.
- ✔ Study ways to **make the spacecraft more robust against the de-tumble event**, such as **using retractable solar arrays**.

Asteroid Deflection Demonstrations

- ✔ Conduct **further studies of the enhanced gravity tractor, ion beam deflection, and post-mission kinetic impactor deflection** concepts using the ARV with or without the returned mass to compare costs, effectiveness, and applicability to ARM.
- ✔ **Demonstrate robotic spacecraft mechanisms** (e.g. surface samplers, excavators, anchors) to support planetary defense.
- ✔ Consider **demonstrating other deflection concepts that do not affect the ARV**, if budget permits.
  - **Robotic spacecraft mechanisms** (anchoring, excavation)
  - Possible testing of **some of the hardware and operational concepts** needed for nuclear detonation approaches.

Asteroid Redirection Systems

- ✔ Establish a concise set of mission objectives and figures of merit, **including extensibility, sustainability, and commercialization** considerations.
- ✔ Perform an **assessment of the various mission enhancement options**, including technology push vs. using low-risk mature technologies.
- ✔ Focus risk reduction activities so that they are consistent with the mission concept approach and **commercial utility of technology development**.
- ✔ Conduct **follow-on studies of integrated sensing systems** that can support multiple mission phases and broader NASA exploration needs.
- ✔ **Improve coordination with the small body science community.**
- ✔ Establish an approach for **addressing business case and partnership opportunities**.

Green Font: Part of BAA or AGC. ✔ At least partially incorporated into ARM/AGC follow-on activities.

Findings From the Asteroid Initiative Workshop

Partnership and Participatory Engagement

Asteroid Redirect Mission

- **Consider Cooperative Research and Development Agreements (CRADAs)** as they have been successful in the past.
- ✔ **Consider milestone-base contractual approaches** similar to COTS and ILDD.
- ✔ **Consider data buys or incentive prizes** for acquisition of asteroid data/information.
- ✔ Learn what motivates industry partners and **understand the different phases of the mining business** to inform mission design and architecture.
- ✔ Establish clear mission objectives, stick to them, and **define what roles participants will play** so industry can organize properly.
- ✔ **Develop specific technology roadmaps** so industry and universities can focus their energy on gaps.

Grand Challenge

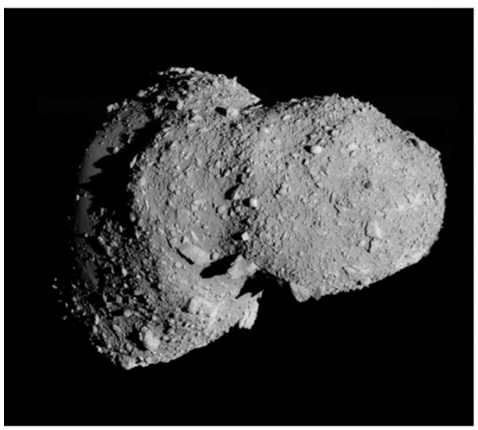
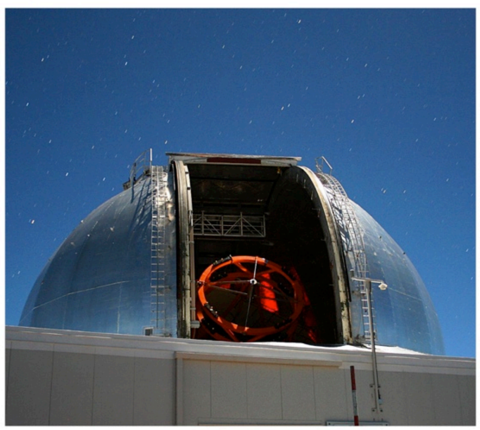
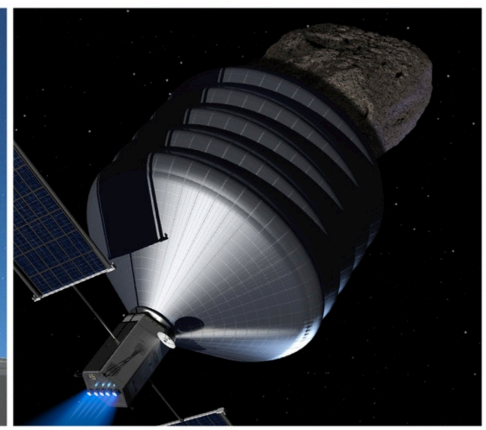
- ✔ Consider **forums for engaging the public** in two-way policy conversations.
- ✔ Build momentum through the **use of smaller demos** that can culminate in larger demos to leverage the shared progress.
- **Explore conversations about risk** and learn from the natural disaster response community.

Green Font: Part of BAA or AGC. ✔ At least partially incorporated into ARM/AGC follow-on activities.

National Aeronautics and Space Administration

Asteroid Redirect Mission
Building Human Exploration Capabilities

Steve Stich-Deputy Director JSC Engineering
March 26, 2014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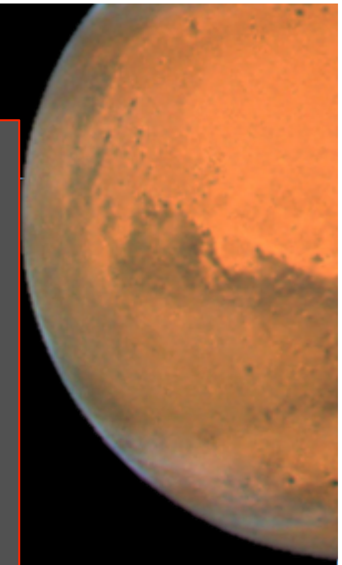
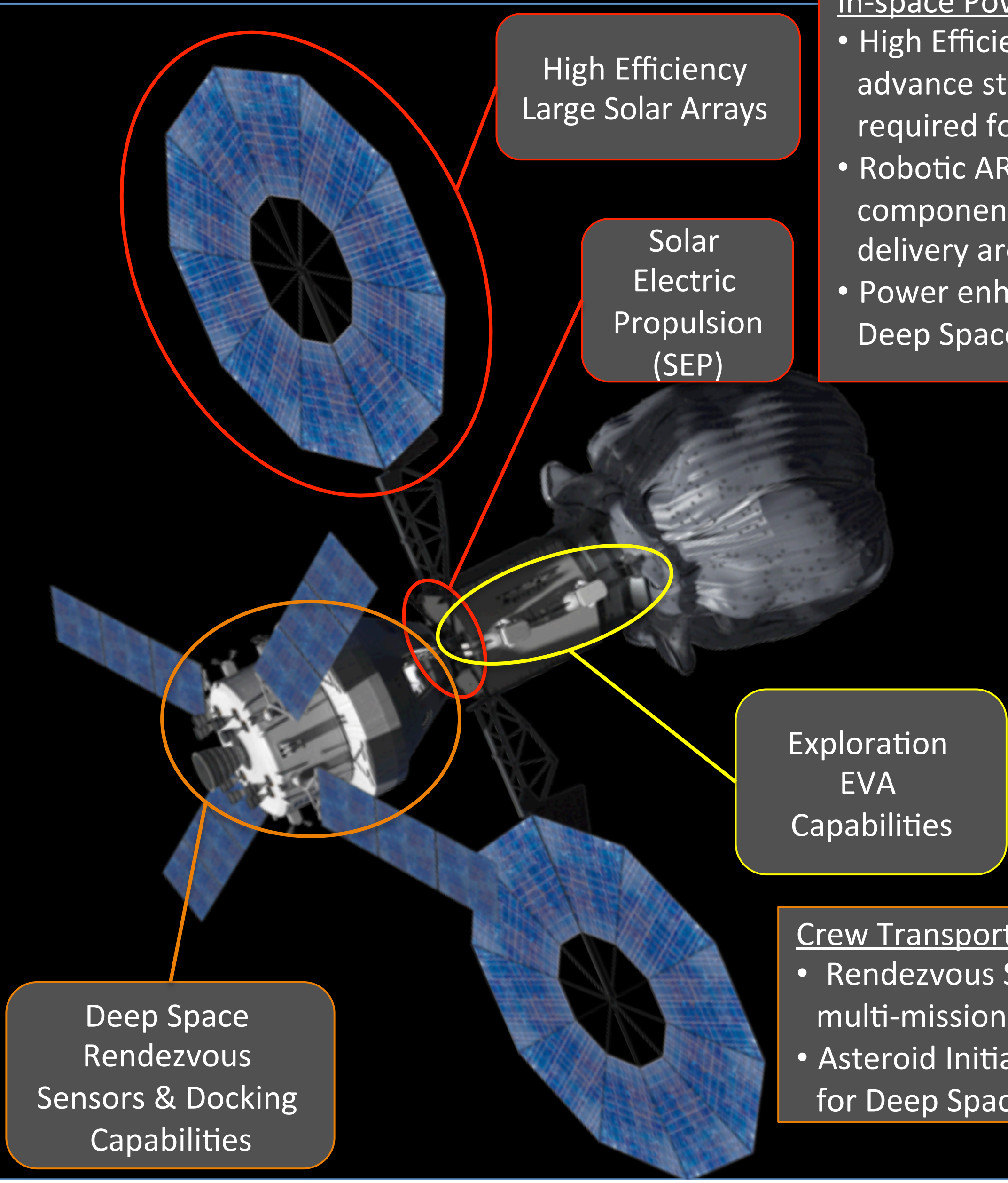
Asteroid Redirect Mission Provides Capabilities For Deep Space/Mars Missions





<u>In-space Power and Propulsion</u> :

- High Efficiency Solar Arrays and SEP advance state of art toward capability required for Mars
- Robotic ARM mission 40kW vehicle components prepare for Mars cargo delivery architectures
- Power enhancements feed forward to Deep Space Habitats and Transit Vehicles

<u>EVA</u>:

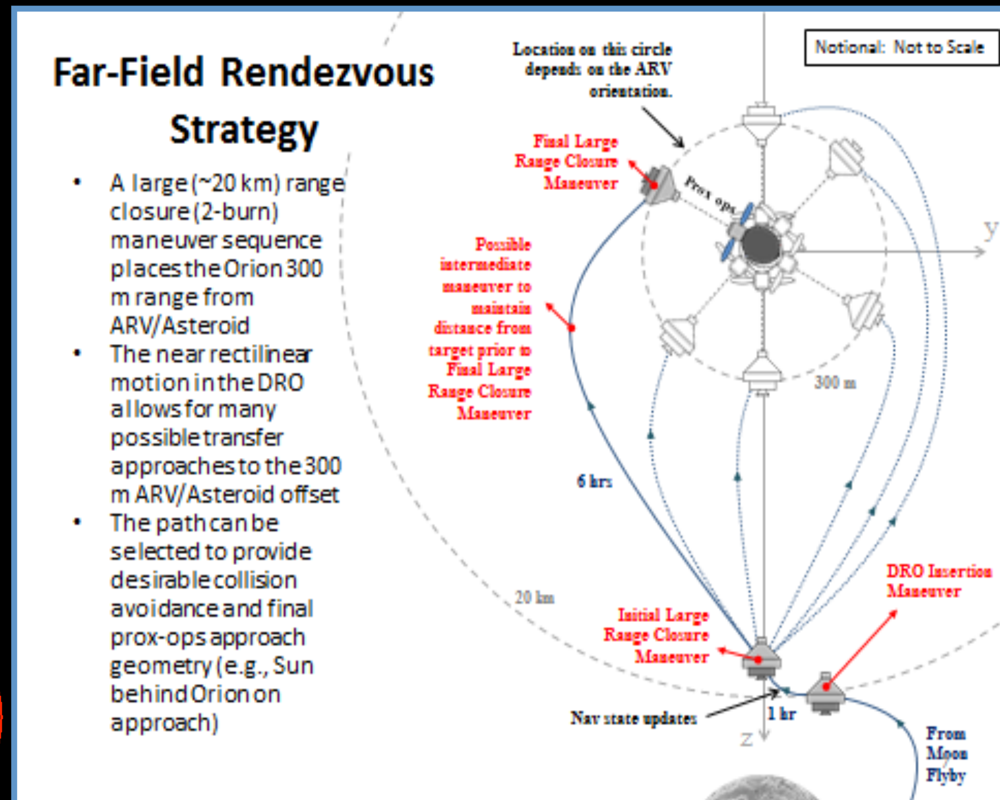
- Build capability for future exploration through Primary Life Support System Design which accommodates Mars
- Test sample collection and containment techniques including planetary protection
- Follow-on missions in DRO can provide more capable exploration suit and tools

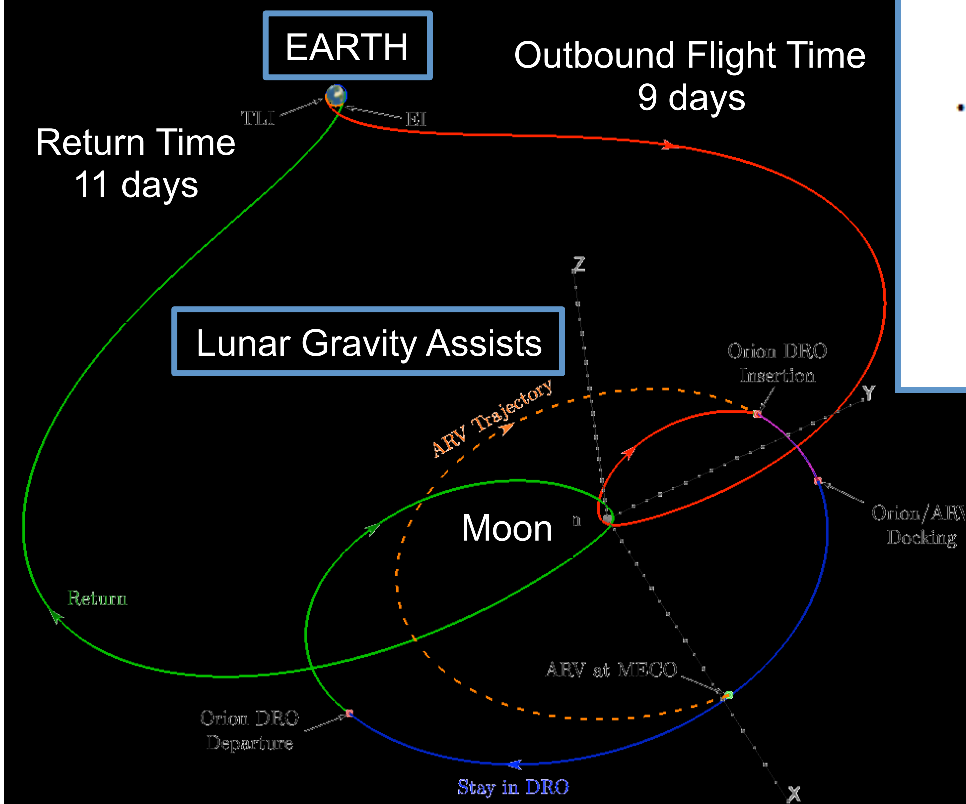
<u>Crew Transportation and Operations:</u>

- Rendezvous Sensors and Docking Systems provide a multi-mission capability needed for Deep Space and Mars
- Asteroid Initiative in cis-lunar space is a proving ground for Deep Space operations, trajectory, and navigation.

Trajectory, Rendezvous, and Proximity Operations

- Common Rendezvous/prox-ops sensors leveraging Space Shuttle Detailed Tests
- Rendezvous /proximity operations maneuvers result largely in rectilinear motion
- Trajectory, launch window, rendezvous, and navigation techniques enable Mars



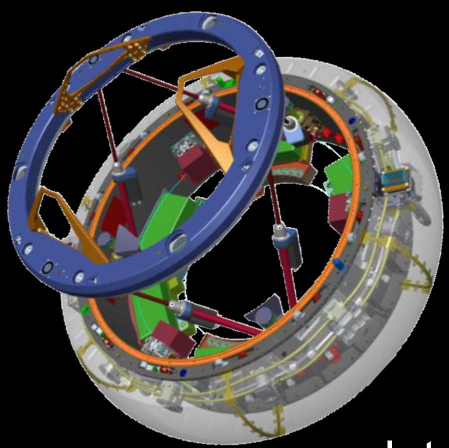


STORRM Camera Image

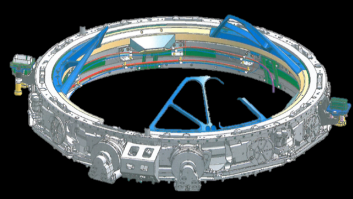
STORRM LIDAR Images

Docking System

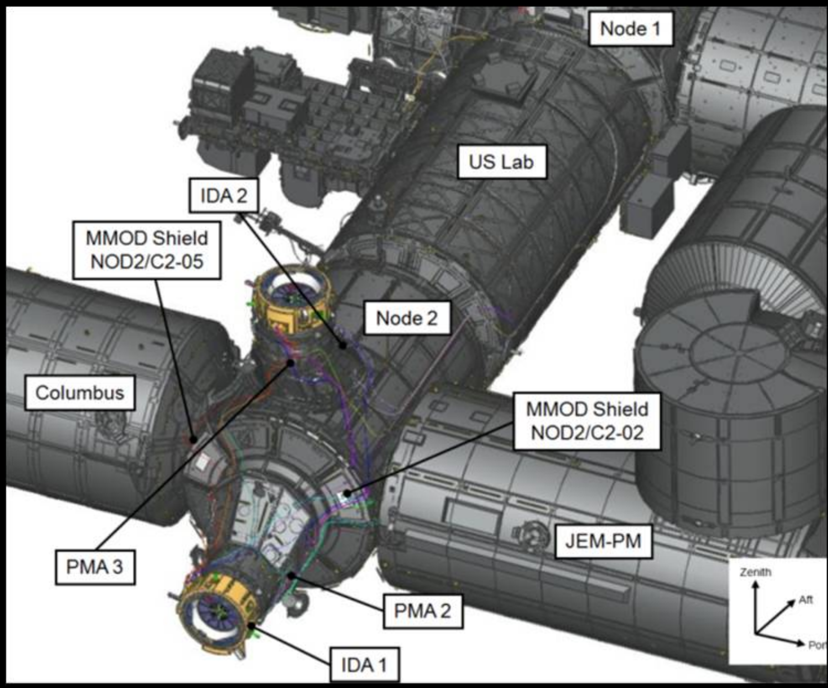
- **Docking System for Orion and Robotic Spacecraft leverages development of International Docking System Block 1**
- **All Mars/Deep Space Architectures will require some form of autonomous docking**



Orion Active Docking Mechanism



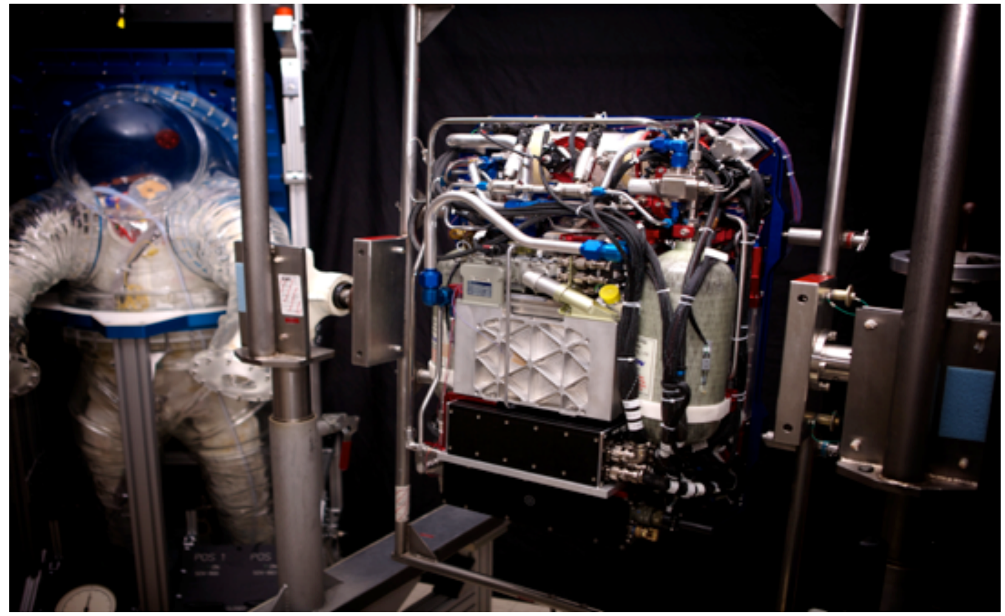
Robotic Spacecraft Passive Docking Mechanism

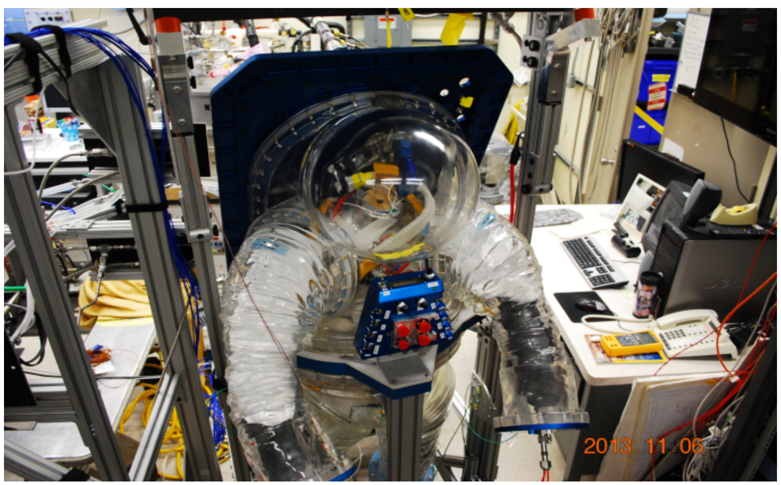


- International Docking Adapter will create a docking port on ISS to provide power and data utility connections to visiting vehicles
- Beginning FY14 study with ISS Program to evaluate Block I to Block II:
  - Voltage and avionics
  - Deep space environment
  - Mass reduction opportunities
  - Overall system design efficiency

EVA Suit and Primary Life Support System (PLSS)

- **Exploration PLSS- capable with small modifications of ISS EMU, Exploration Suit, or M-CES with architecture that is Mars capable**
  - PLSS 2.0 prototype completed in FY13
  - Variable Oxygen Regulator flammability testing completed at White Sands Test Facility
  - FY14 work includes integrated metabolic and functional testing and fabrication of a PLSS/MACES integration kit will be completed in FY14





Liquid Cooling and Ventilation Garment Heated Manikin in Space Suit Simulator

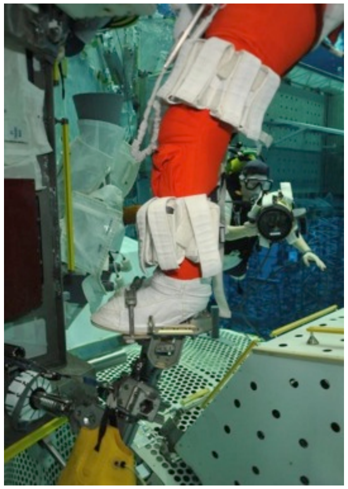
Variable Oxygen Regulator Testing at WSTF

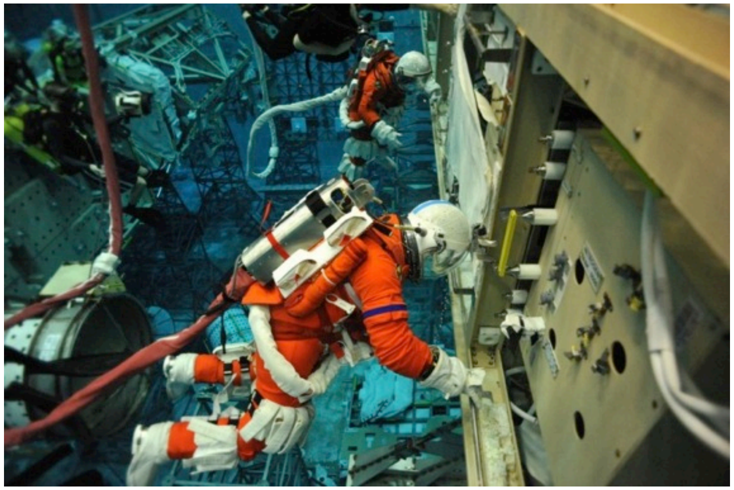
MACES with PLSS and EVA Suit Kit

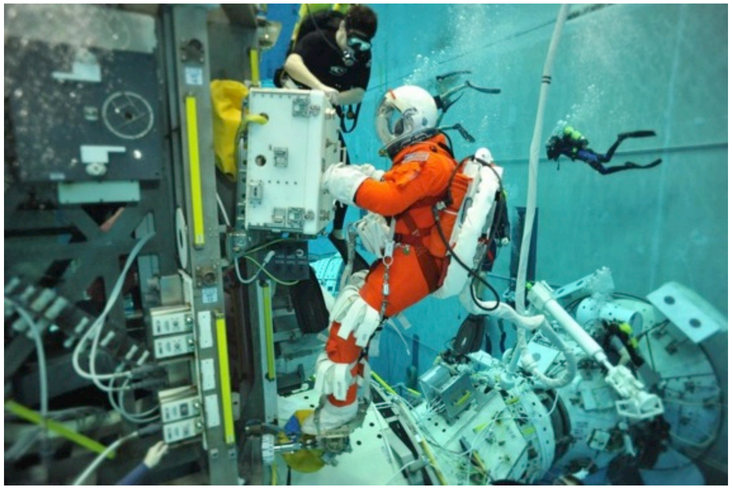
February 2014 EVA Testing in NBL

- February 2014 testing focused on first portion of spacewalk (egress, translation, worksite prep):
  - 2 Crew Capability
  - Enhanced Suits with arm bearing and positioning
  - EMU Boots
  - Portable Foot Restraint

- April test series will emphasize sample capture and worksite stability



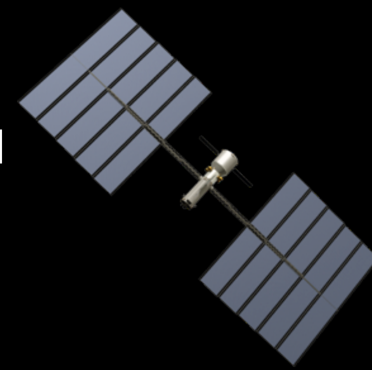




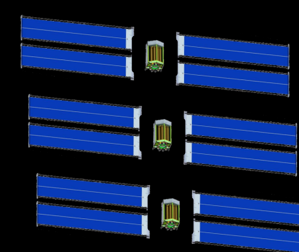
Use of ARM Solar Electric Propulsion (SEP)

- Previous assessments have shown that human Mars missions utilizing a single round-trip monolithic habitat requires very high power SEP (approximately **1 MW total power)**
- Alternate architecture concepts enable ARM derived SEP to be used.
  - Pre-deploy crew mission assets to Mars utilizing high efficient SEP, such as
    - Orbit habitats: Supports crew while at Mars
    - Return Propulsion Stages or return habitats
    - Exploration equipment: Unique systems required for exploration at Mars.
  - High thrust chemical propulsion for crew
    - Low-thrust SEP too slow for crew missions
    - Crew travels on faster-transit, minimum energy missions: 1000-day class round-trip (all zero-g)

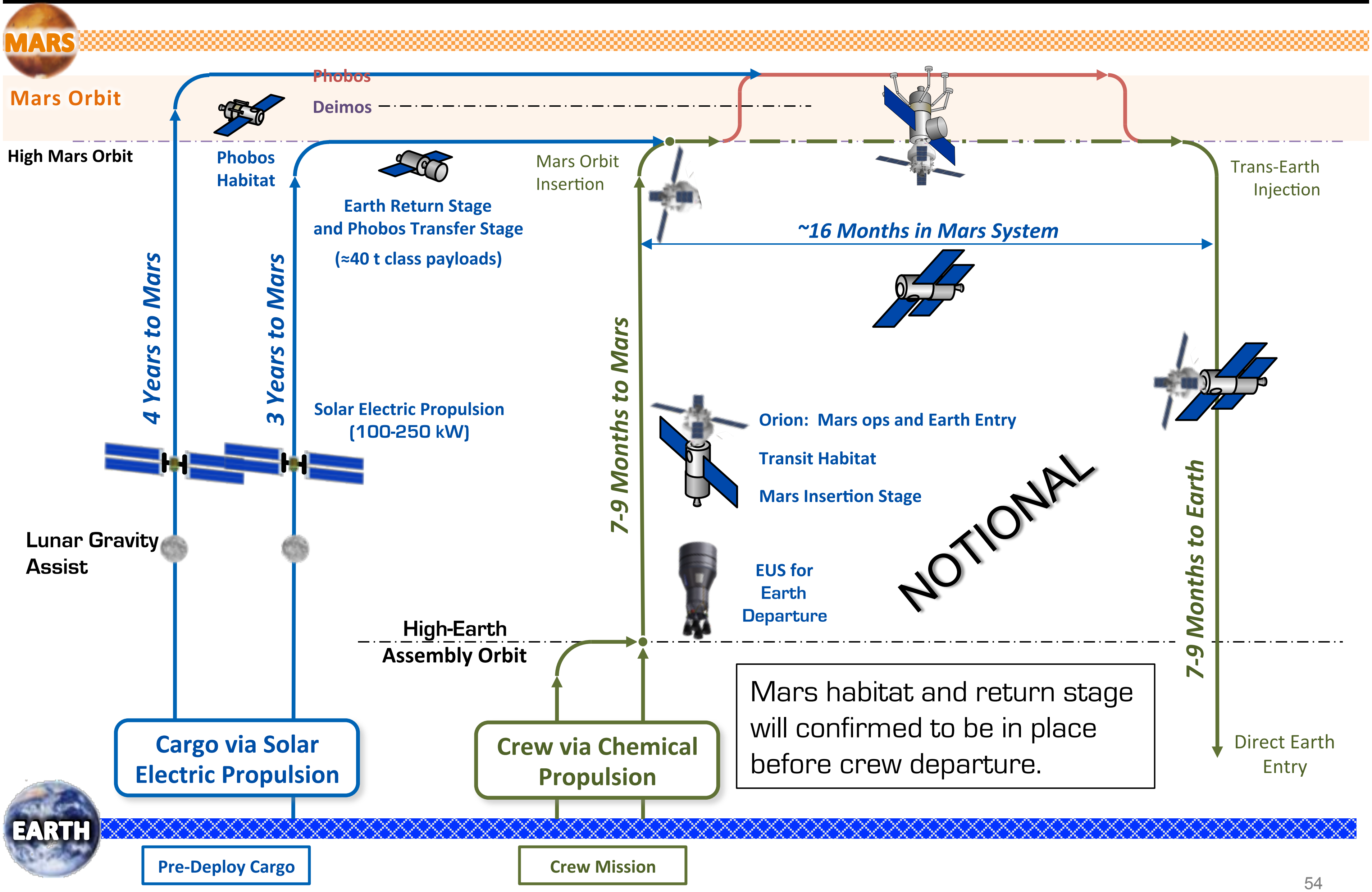
One Very Large SEP



Multiple ARM derived SEPs (100-250 Kw Class)



Notional ARM Derived Phobos Mission



ISS and ARM Provides First Steps to Mars

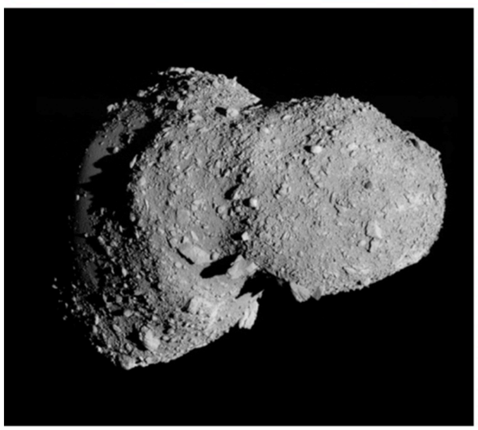
	Mission / Sequence	Current ISS Mission	Asteroid Redirect Mission	Long Stay In Deep Space	Mars Orbit	Mars Surface, Short Stay	Mars Surface, Long Stay
Mars Destination Capabilities	In Situ Resource Utilization & Surface Power						X
	Surface Habitat						X
	Entry Descent Landing, Human Lander					X	X
	Advanced Cryogenic Upper Stage				X	X	X
Initial Exploration Capabilities	Solar Electric Propulsion for Cargo		X	X	X	X	X
	Exploration EVA		X	X	X	X	X
	Crew Operations beyond LEO (Orion)		X	X	X	X	X
	Deep Space Guidance Navigation and Control/Automated Rendezvous		X	X	X	X	X
	Crew Return from Beyond LEO – High Speed Entry (Orion)		X	X	X	X	X
	Heavy Lift Beyond LEO (SLS)		X	X	X	X	X
ISS Derived Capabilities	Deep Space Habitat	*		X	X	X	X
	High Reliability Life Support	*		X	X	X	X
	Autonomous Assembly	*		X	X	X	X

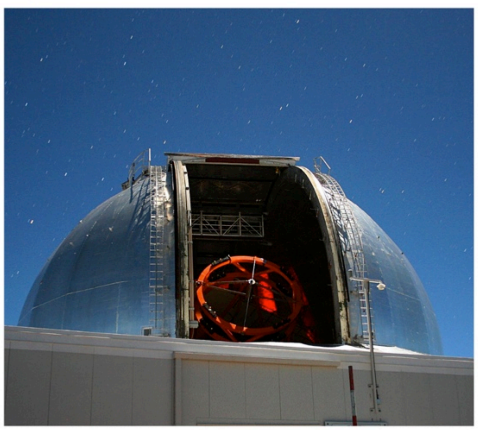
National Aeronautics and Space Administration

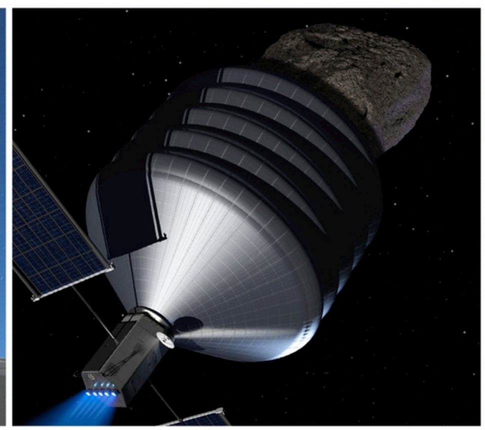
Asteroid Redirect Mission Extensibility

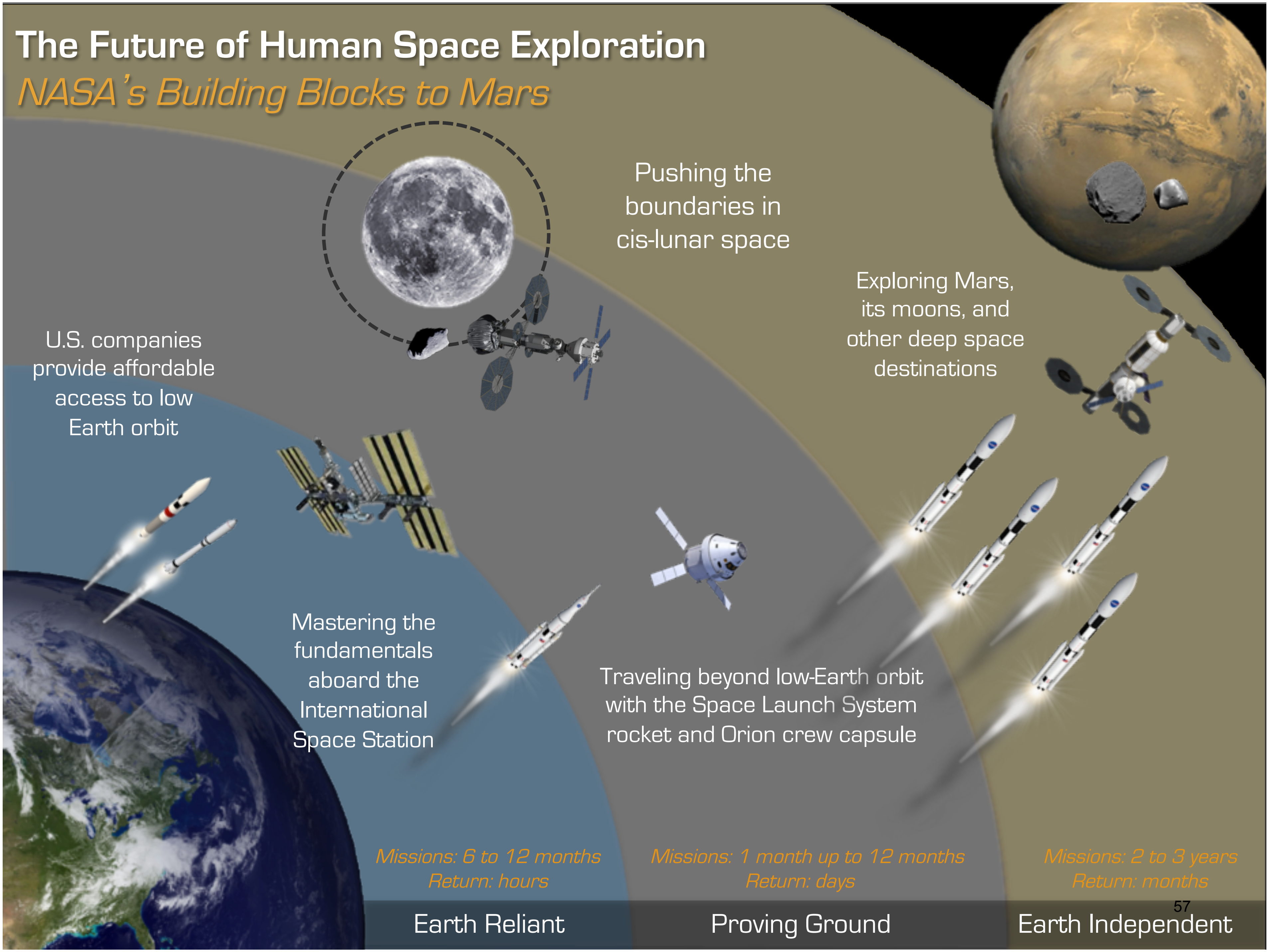
Jason Crusan, Director, Advanced Exploration Systems

March 26, 2014



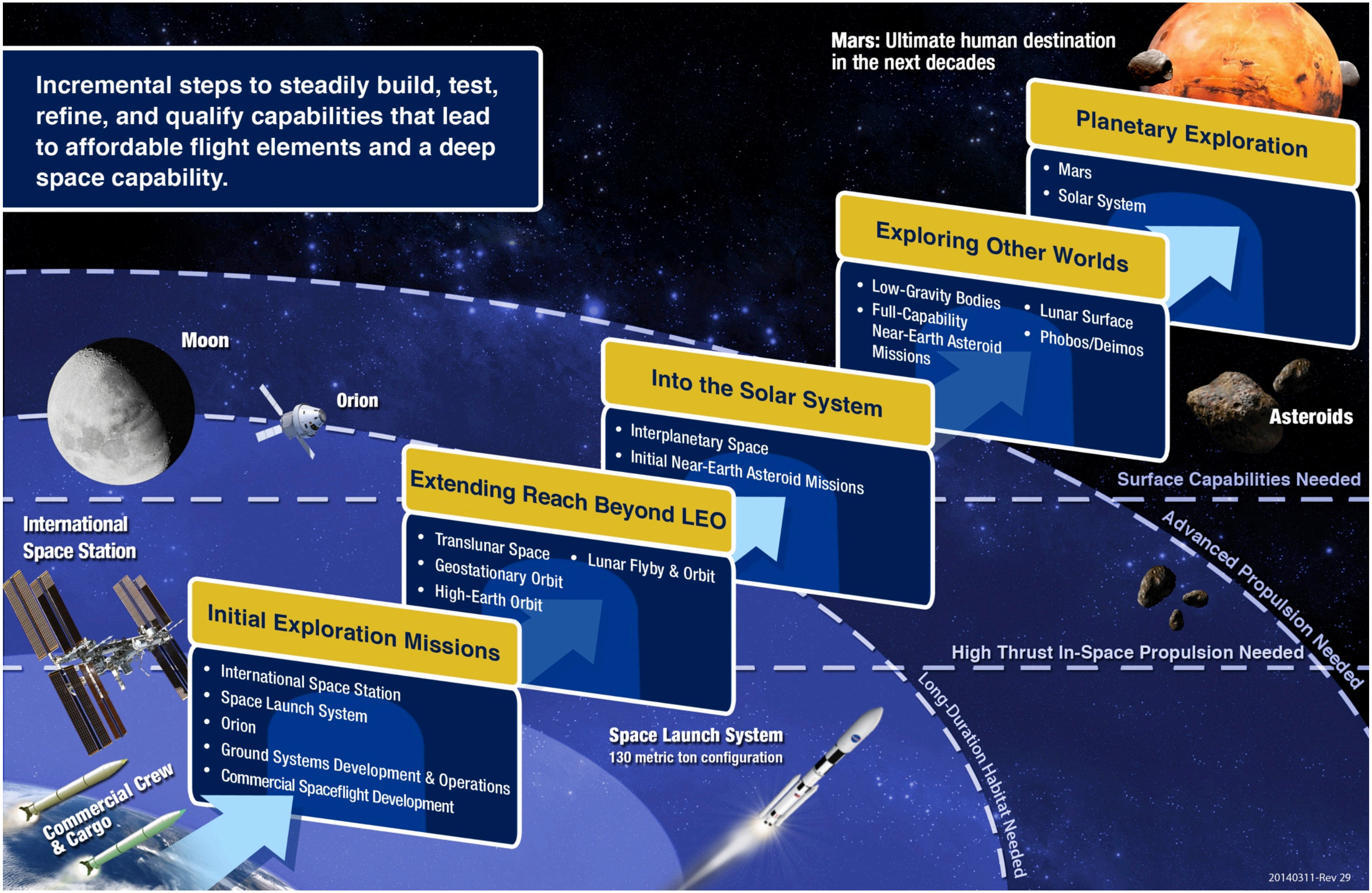






The Future of Human Space Exploration
NASA's Building Blocks to Mars
Pushing the boundaries in cis-lunar space
Exploring Mars, its moons, and other deep space destinations
U.S. companies provide affordable access to low Earth orbit
Mastering the fundamentals aboard the International Space Station
Traveling beyond low-Earth orbit with the Space Launch System rocket and Orion crew capsule
Missions: 6 to 12 months
Return: hours
Missions: 1 month up to 12 months
Return: days
Missions: 2 to 3 years
Return: months
Earth Reliant
Proving Ground
Earth Independent

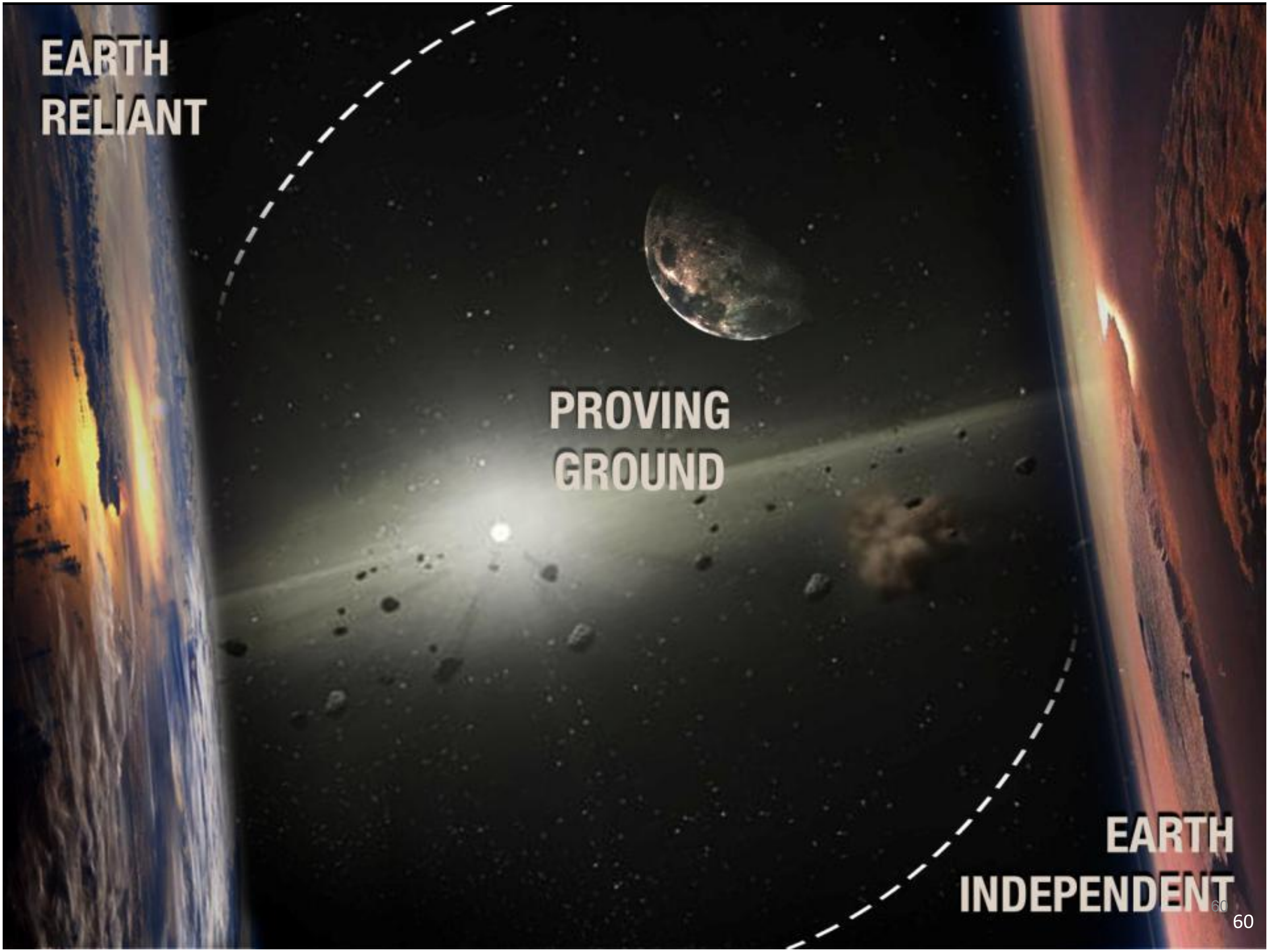
The Capability Driven Framework



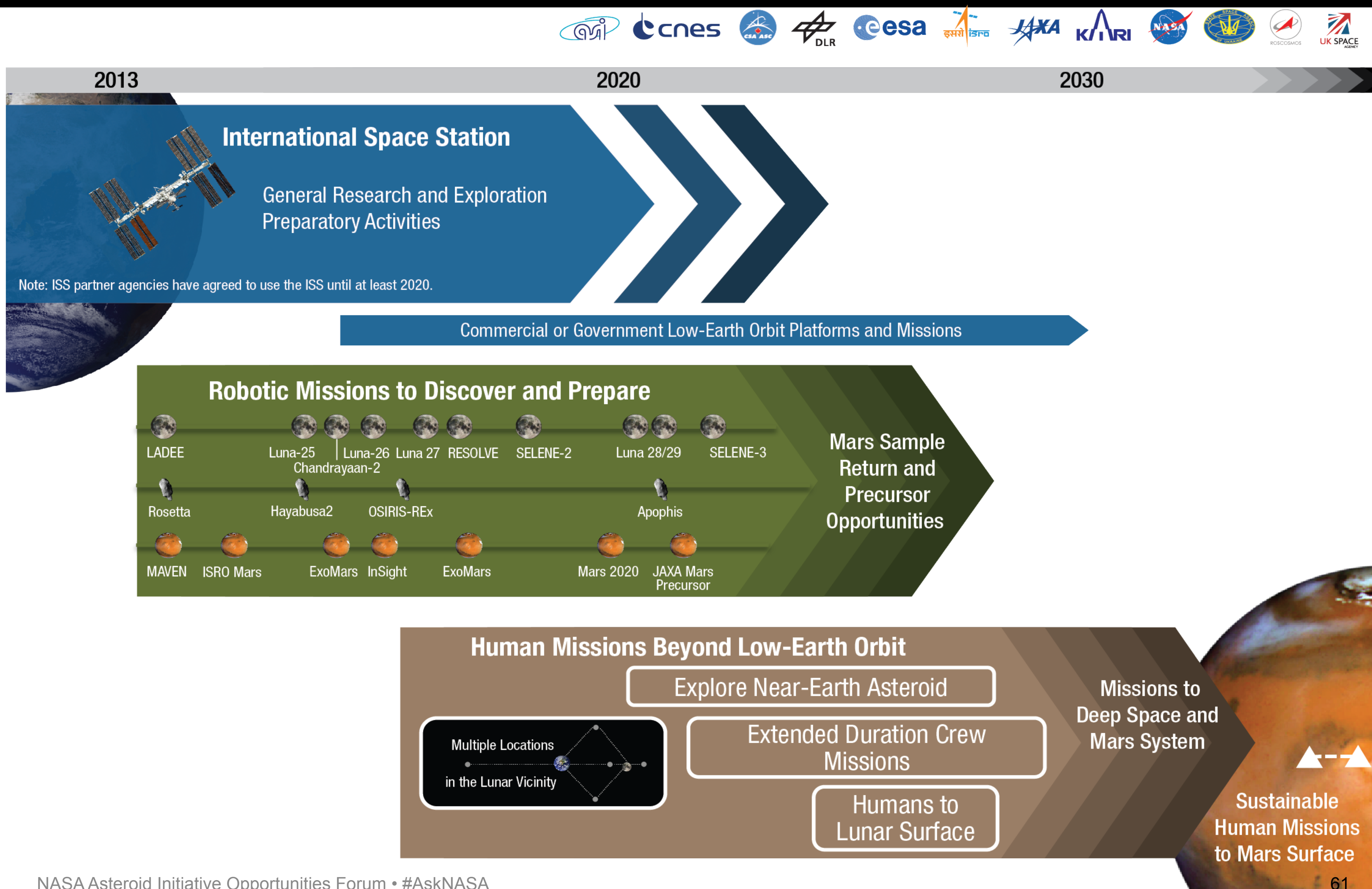
Strategic Principles for Incremental Building of Capabilities

Six key strategic principles to provide a sustainable program:

1. Executable with current ***budget with modest increases.***
2. Application of ***high Technology Readiness Level*** (TRL) technologies for near term, while focusing research on technologies to address challenges of future missions
3. ***Near-term mission*** opportunities with a defined cadence of compelling missions providing for an incremental buildup of capabilities for more complex missions over time
4. Opportunities for ***US Commercial Business*** to further enhance the experience and business base learned from the ISS logistics and crew market
5. ***Multi-use, evolvable*** Space Infrastructure
6. Significant ***International and Commercial participation***, leveraging current International Space Station partnerships


EARTH
RELIANT
PROVING
GROUND
EARTH
INDEPENDENT

Global Exploration Roadmap



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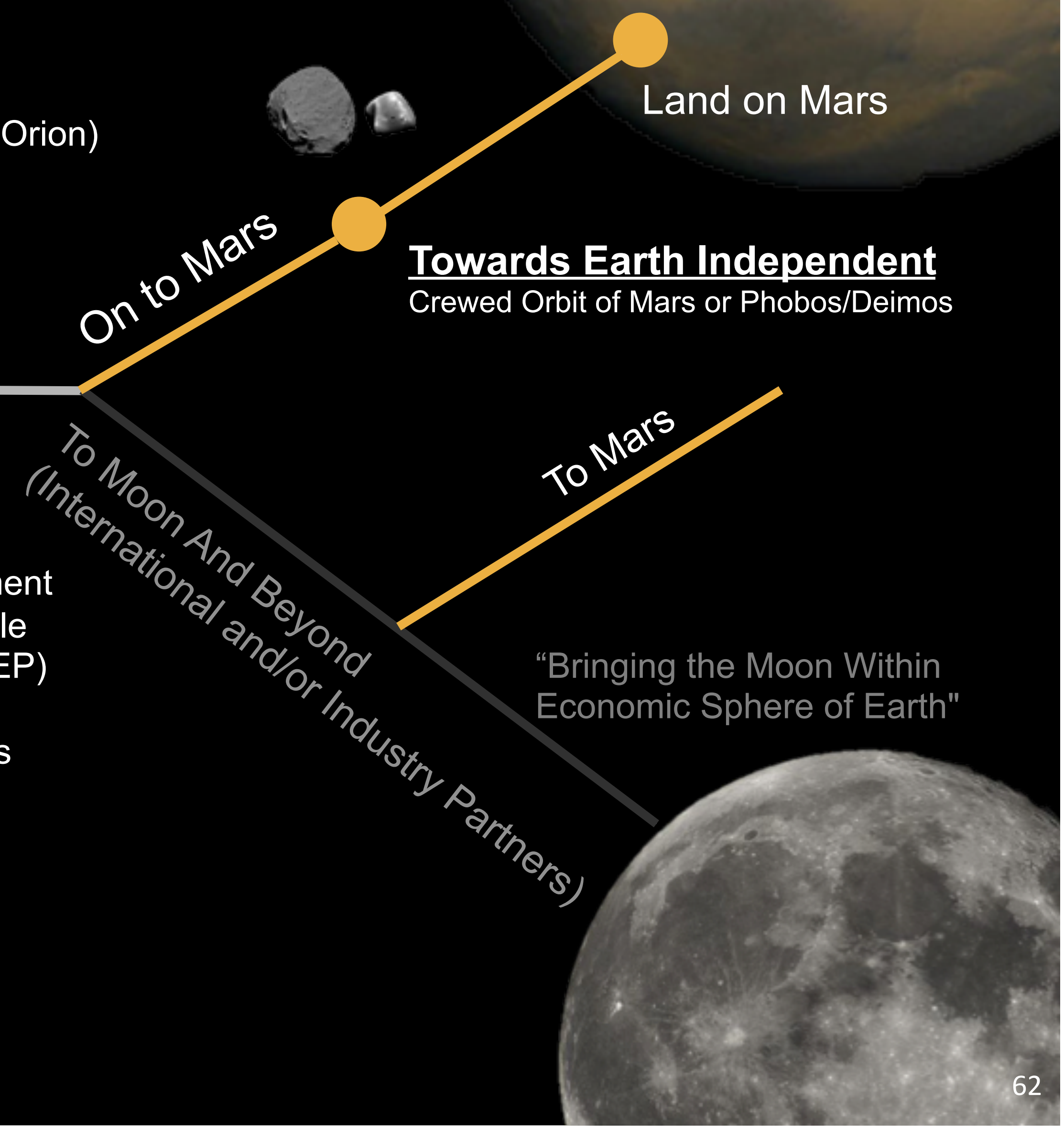
Human Exploration Pathways

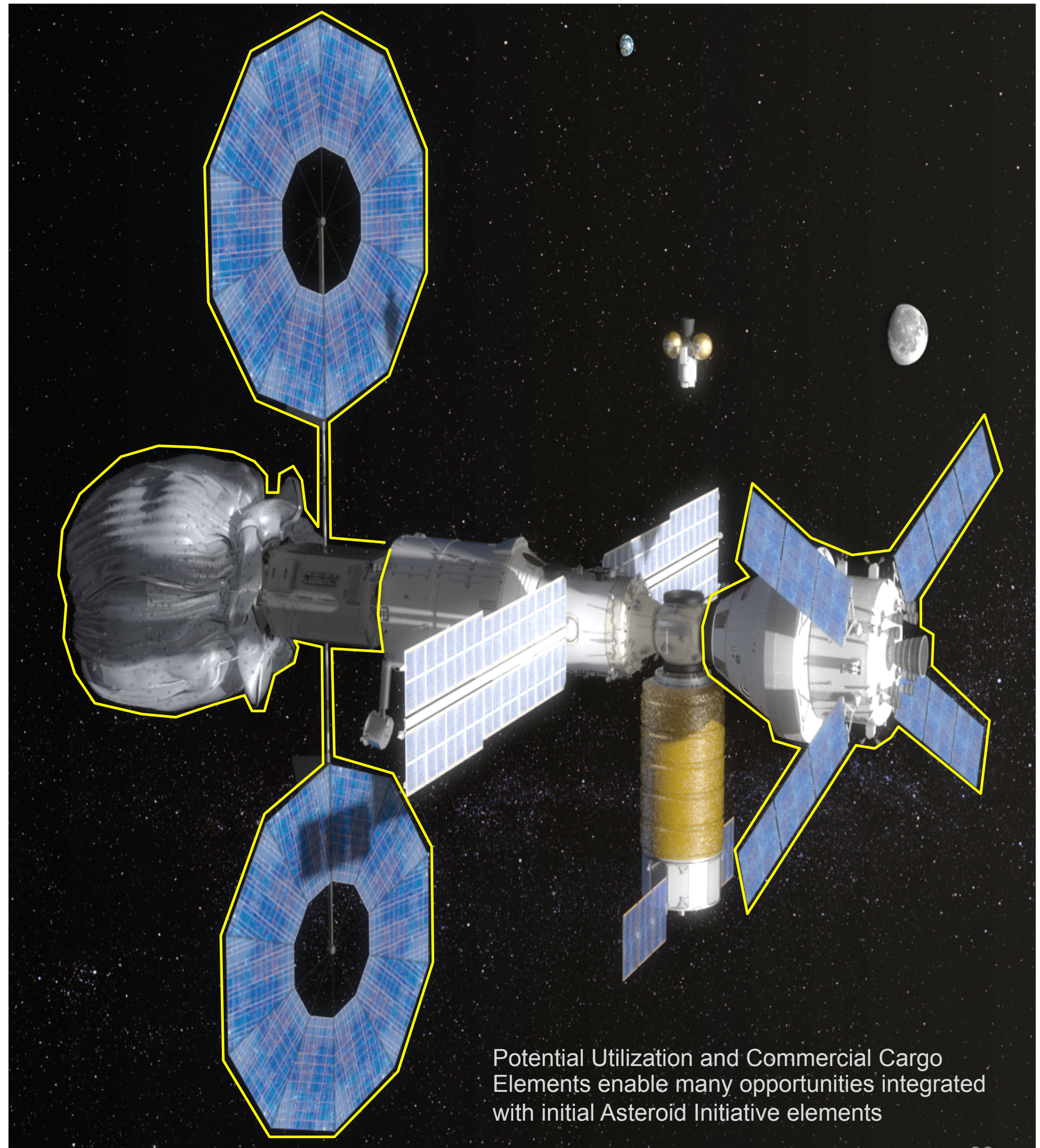
Mastering the Fundamentals
- Extended Habitation Capability (ISS)
  - High Reliability Life Support
- Deep-space Transportation (SLS and Orion)
- Exploration EVA
- Automated Rendezvous & Docking
- Docking System

Pushing the Boundaries
- Deep Space Operations
  - Deep Space Trajectories
  - Deep Space Radiation Environment
  - Integrated Human/Robotic Vehicle
- Advanced In-Space Propulsion (SEP)
  - Moving Large Objects
- Exploration of Solar System Bodies



Further Utilization Enables Broader Participation to Achieve Exploration Goals

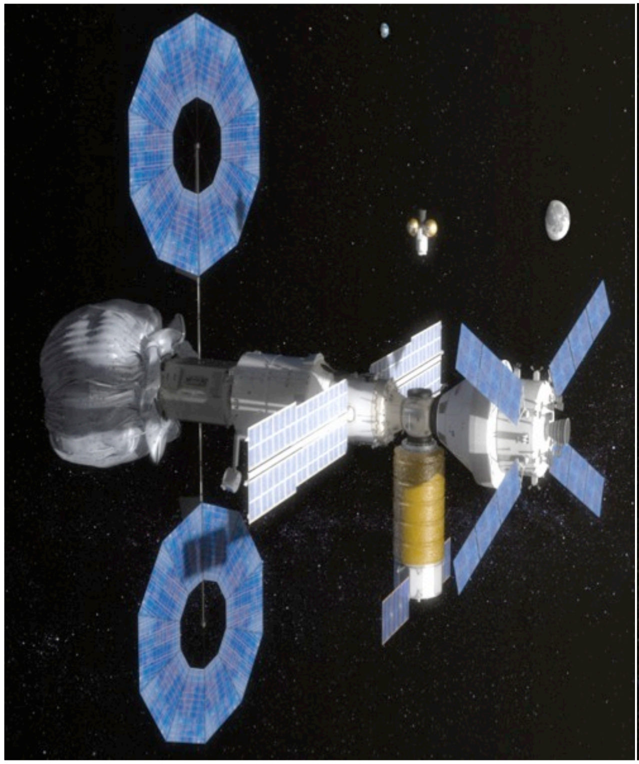
- **Many possible opportunities for further utilization of the Asteroid**
  - Testing of anchoring techniques
  - In-situ Resource Utilization (ISRU) Demonstration
  - Additional Asteroid Sample Collection
  - Lunar and Mars sample return
  - Scientific Experiments
  - Many other possibilities
- **Realization of these opportunities requires additional payload delivery resources**
  - Extending Commercial opportunities beyond low Earth orbit
  - Opportunity for International Partner Contributions
- **Addition of utilization elements provide:**
  - Extended crewed mission duration and additional EVA capability
  - Enhance crew safety with more robust systems and infrastructure



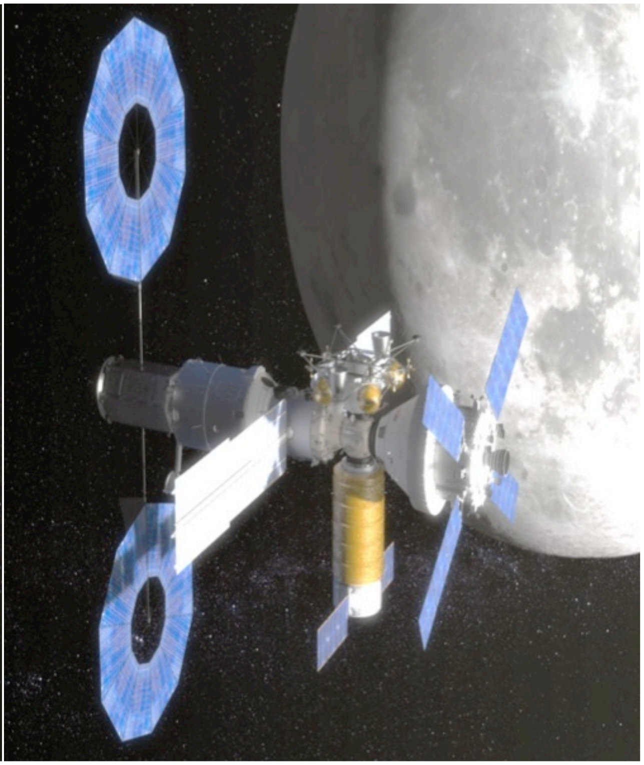
Moon size in image not to scale

Initial Asteroid Initiative Elements

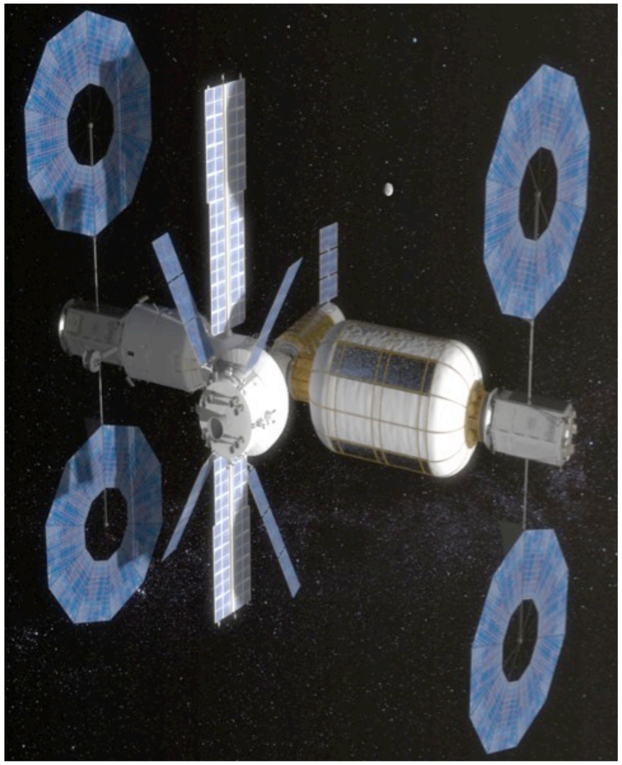
Asteroid Redirect Mission builds upon Orion/SLS to enable Global Exploration Roadmap



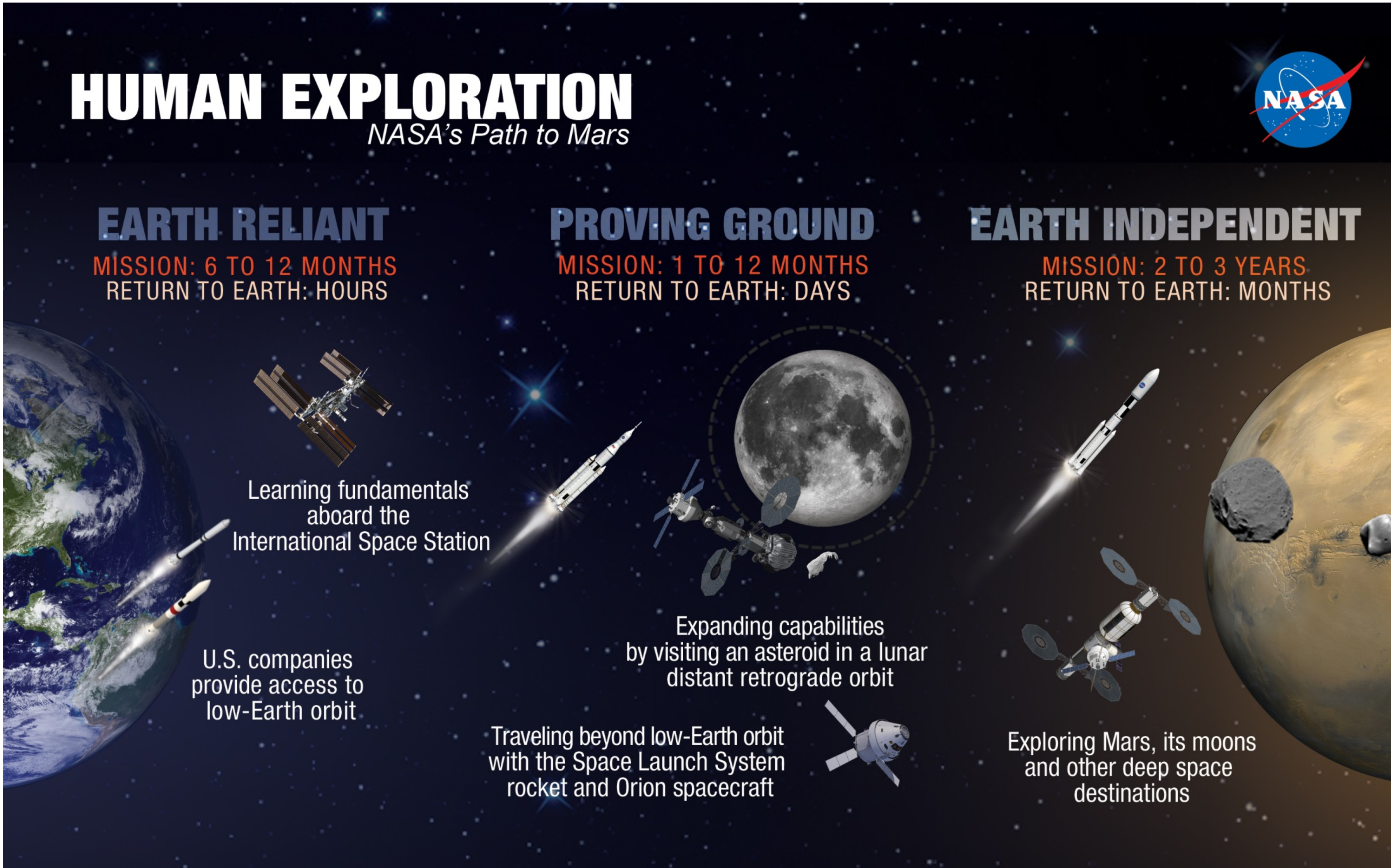
Asteroid Exploitation Missions



Lunar Vicinity Missions



Deep Space Missions



The Asteroid Redirect Mission builds on space station experience and shows how the lunar vicinity serves as a proving ground to demonstrate capabilities and learn to manage the risks of the deep space environment.